

MiniBooNE $\bar{\nu}_\mu$ CCQE and NCE cross sections

Joe Grange
University of Florida
and
Ranjan Dharmapalan
University of Alabama



Outline

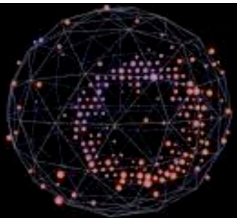


Joe Grange

NuInt 2012

Oct. 25 2012

1. MiniBooNE and $\bar{\nu}$ -mode beam
 - wrong-sign background
2. Neutral-current elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
3. Charged-current quasi-elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
4. Combined measurements
5. Summary



Outline



Joe Grange

NuInt 2012

Oct. 25 2012

- I. MiniBooNE and $\bar{\nu}$ -mode beam
 - wrong-sign background
2. Neutral-current elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
3. Charged-current quasi-elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
4. Combined measurements
5. Summary



Flux prediction

Joe Grange

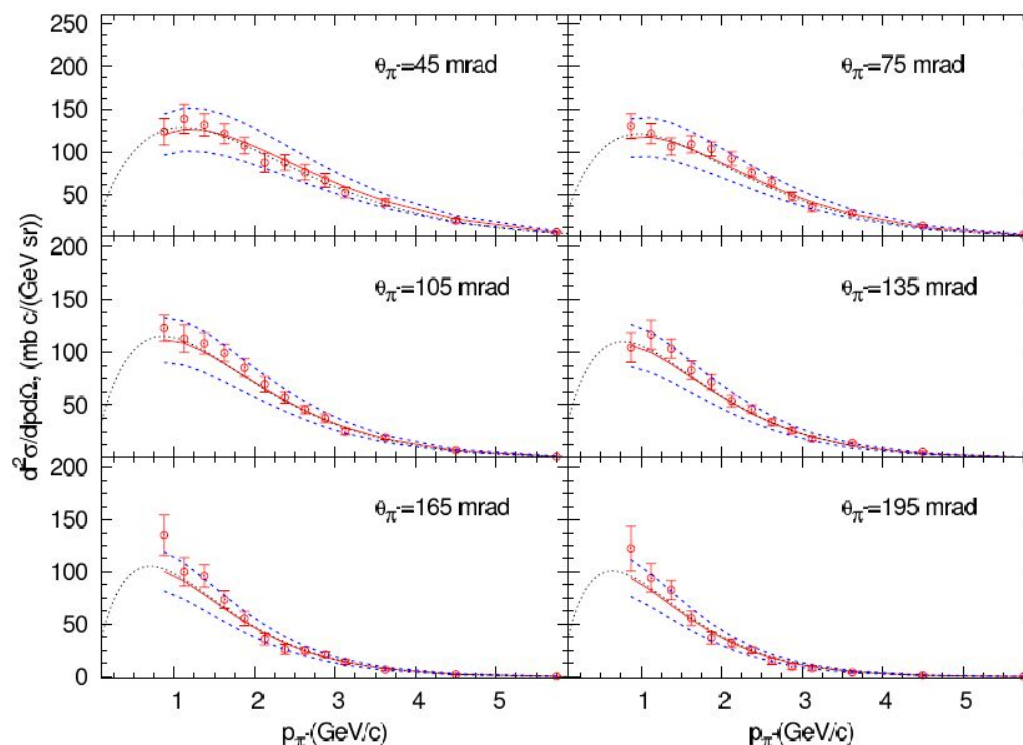
NuInt 2012

Oct. 25 2012

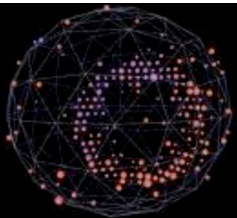


- ▶ Secondary π^- production based exclusively on external data - no *in situ* tuning
 - both π^- and π^+
- ▶ These dedicated data allow for absolute MB σ measurements

π^- production



HARP collaboration,
Eur. Phys. J. C **52** 29 (2007)



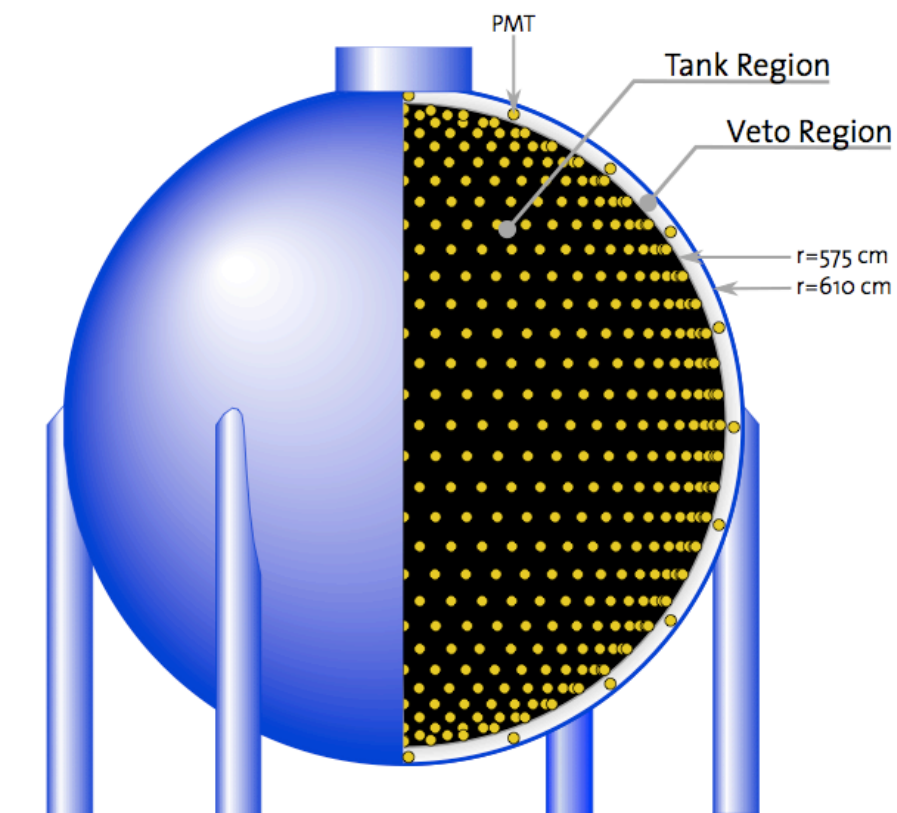
Detector



Joe Grange

NuInt 2012

Oct. 25 2012



Nucl. Instr. Meth. A599, 28 (2009)

- ▶ Primarily a Cherenkov detector, best at reconstructing leptons.
- ▶ However we've shown late light can be used to reconstruct protons well (NCE measurement - more later).



- ▶ Use Llewelyn-Smith expressions for elastic scattering on free nuclei

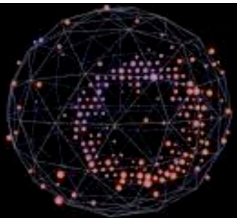
Phys. Rep. 3, 261 (1972)

- ▶ Relativistic Fermi Gas (RFG) model: bound nucleon targets treated as **independent particles** subject to binding energy and global Fermi momentum Nucl. Phys. B43, 605 (1972)

- FF values set by (e,e') scattering data
- introduce empirical Pauli blocking scale k

- ▶ Single π production: Rein-Sehgal model

Ann. Phys. 133, 79 (1981)

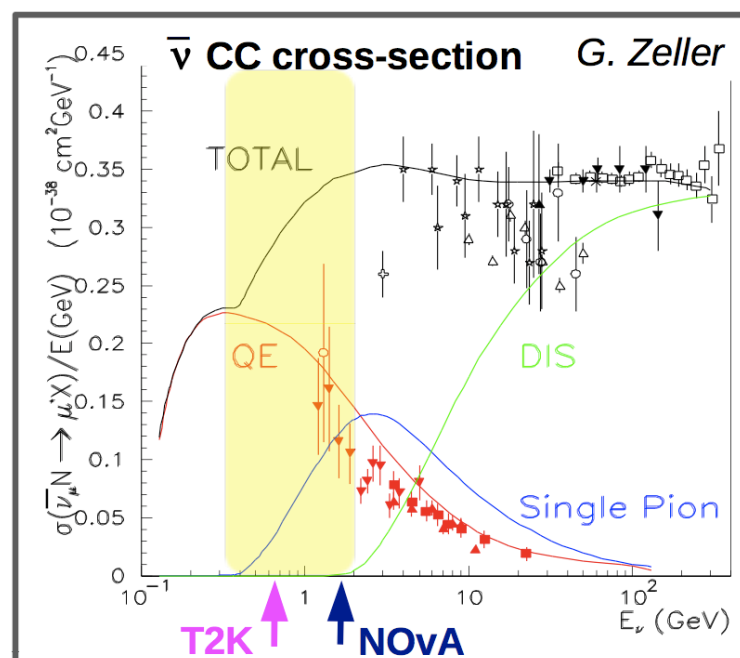
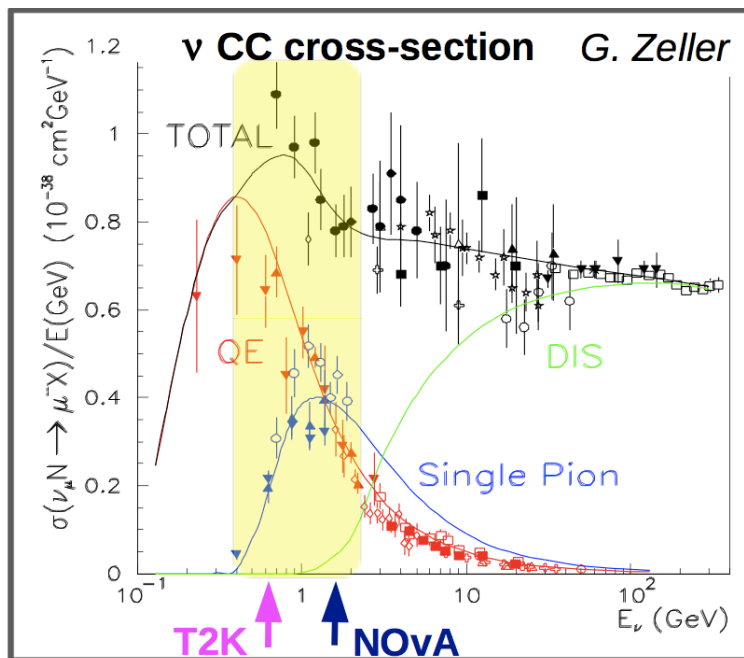


Pre-MiniBooNE σ 's

Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Sparse measurements around MiniBooNE energies
- ▶ Need as much input as possible for successful oscillation program

- ▶ No sub-GeV anti-neutrino σ 's
 - ▶ vital for future CPV measurements
- ▶ First CC + NCE sub-GeV anti-neutrino measurements today!



v-mode rate

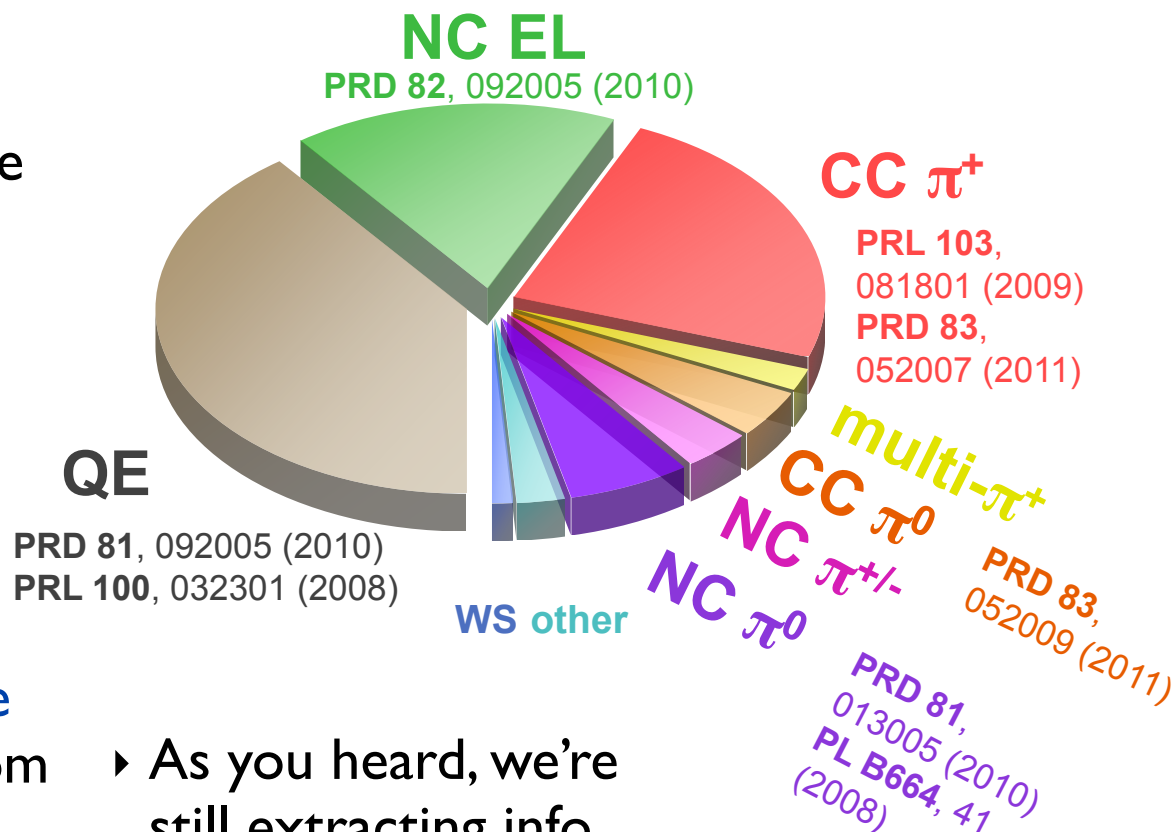
Joe Grange

NuInt 2012

Oct. 25 2012

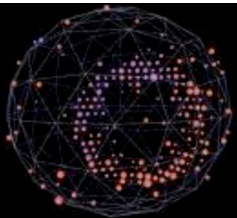


- ▶ MiniBooNE has published ~90% of the total v-mode rate,



- ▶ Lots of interest: more than 500 citations from these papers

- ▶ As you heard, we're still extracting info. from v-mode data (M.Tzanov's talk)



$\bar{\nu}$ -mode rate

Joe Grange

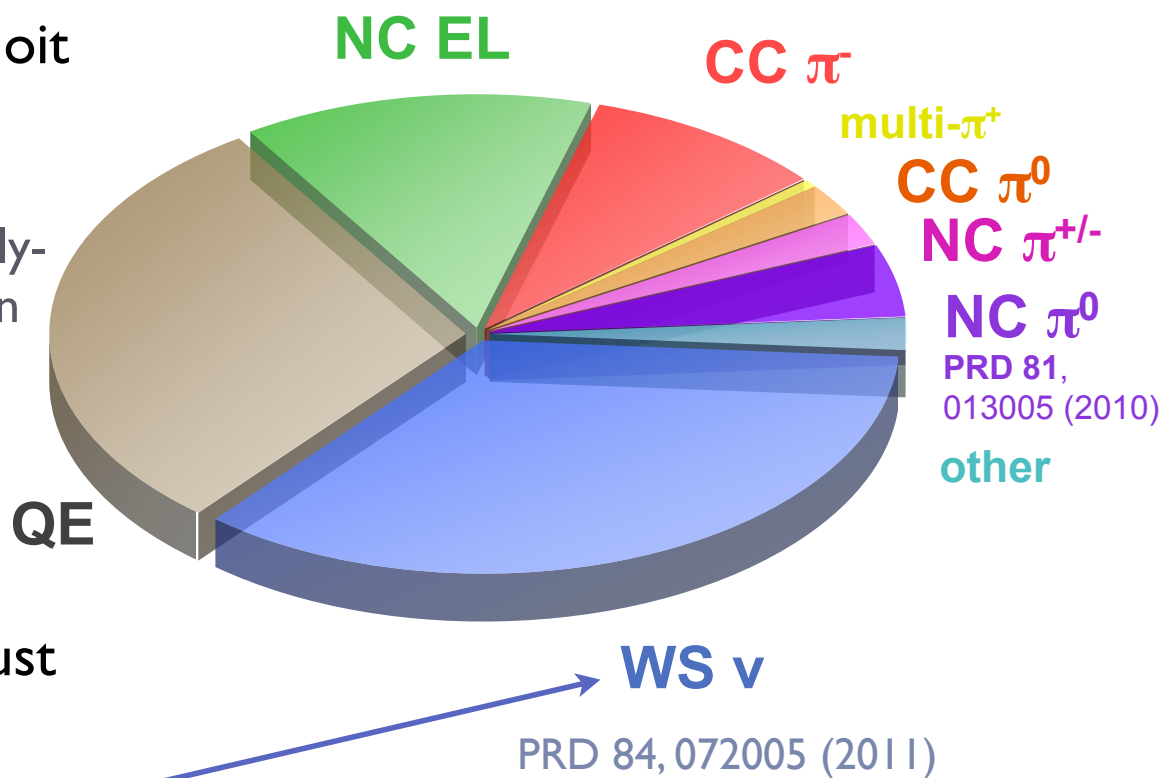
NuInt 2012

Oct. 25 2012



- ▶ To complete MiniBooNE σ program, must fully exploit unprecedented anti- ν statistics

- 1.0×10^{21} POT in a mostly-unexplored energy region



- ▶ Before able to make precision anti- ν_μ σ 's, must deal with largest background: wrong-sign ν_μ



Wrong-sign background

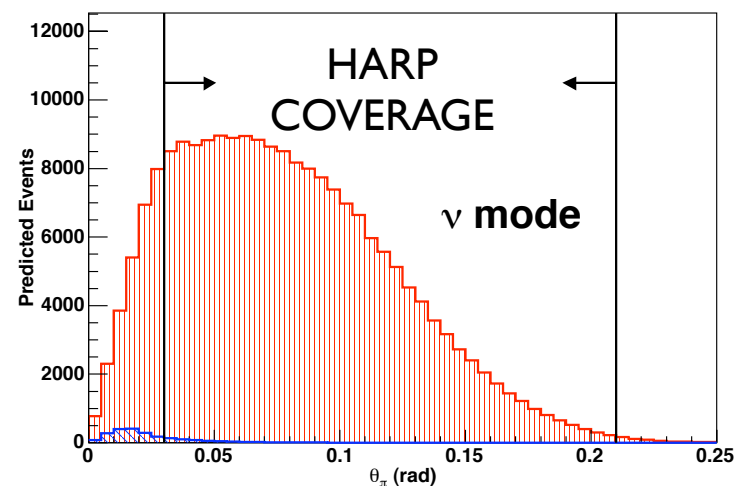
Joe Grange

NuInt 2012

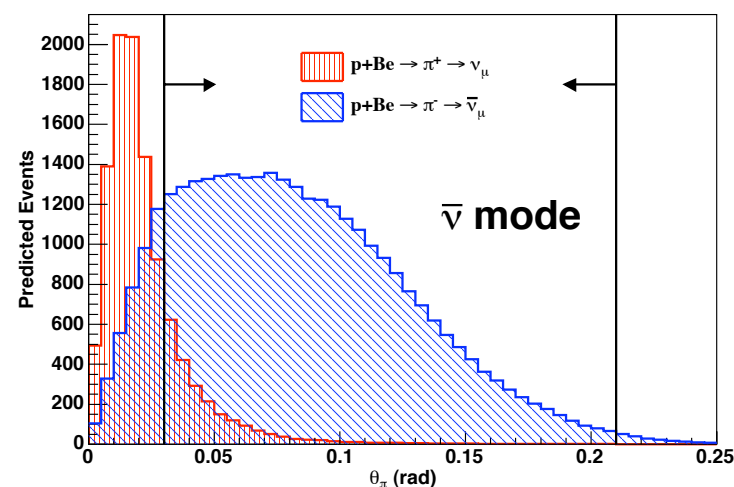
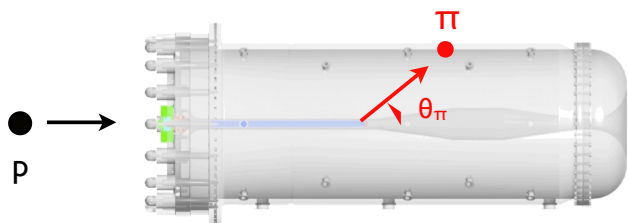
Oct. 25 2012



- ▶ ν_μ parent π^+ production in **anti- ν mode** (“wrong signs”) mostly not covered by HARP (right)
 - overall rate highly uncertain!



- ▶ Moreover, accepted π angle a mild function of energy
 - need to check flux spectrum!





Wrong-sign measurements



Joe Grange

NuInt 2012

Oct. 25 2012

- ▶ Other detectors employ magnetic field to separate ν_μ / anti- ν_μ
 - MiniBooNE unmagnetized, must use statistical techniques
- ▶ General strategy: isolate samples sensitive to ν_μ beam content, apply measured σ 's from neutrino-mode data (CCQE, CC π^+)

$$\frac{\text{Rate}^{\text{data}}}{\text{Rate}^{\text{sim}}} = \frac{\Phi^{\text{true}} \times \sigma^{\text{meas}}}{\Phi^{\text{sim}} \times \sigma^{\text{meas}}} = \frac{\Phi^{\text{true}}}{\Phi^{\text{sim}}}$$

- ▶ Level of data-simulation agreement then reflects accuracy of (**highly-uncertain**) ν_μ flux prediction



Three ν_μ flux measurements



Joe Grange

NuInt 2012

Oct. 25 2012

► Three samples isolated and analyzed:

1. $\text{CC}\pi^+$ sample

anti- ν induced π^- absorbed in the medium (does not decay), so by requiring 1 μ , 2 decay electrons (one each from μ and π^+ decay), get $> 80\%$ purity sample of ν_μ events

2. Scale samples consisting of μ -only and $\mu+e$ for ν_μ , anti- ν_μ content

ν_μ CC events have 8% capture rate in mineral oil

3. Backward scattering region in CCQE sample

anti- ν CCQE expected to be much more forward-going



Three ν_μ flux measurements



Joe Grange

NuInt 2012

Oct. 25 2012

► Three samples isolated and analyzed:

1. $\text{CC}\pi^+$ sample

anti- ν induced π^- absorbed in the medium (does not decay), so by requiring 1 μ , 2 decay electrons (one each from μ and π^+ decay), get $> 80\%$ purity sample of ν_μ events

2. Scale samples consisting of μ -only and $\mu+e$ for ν_μ , anti- ν_μ content

ν_μ CC events have 8% capture rate in mineral oil

3. Ba not well understood, results NOT USED to extract anti- ν cross sections

anti- ν Once σ 's better known, could be a powerful technique



Wrong-sign flux results

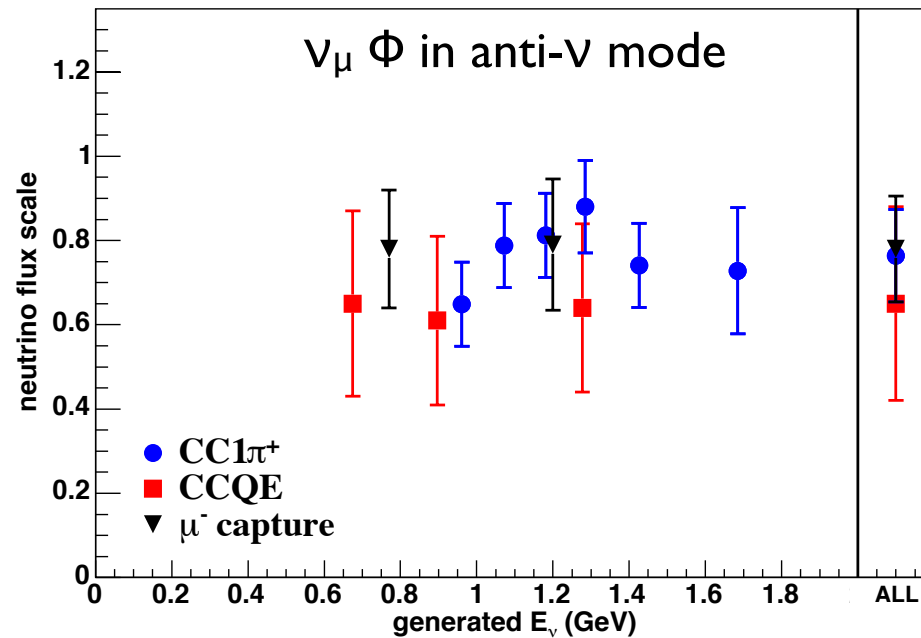
Joe Grange

NuInt 2012

Oct. 25 2012



- Results binned in energy as finely as allowed by statistics
 - nominal prediction $\sim 20\%$ high in normalization, simulated spectrum appears adequate



- predicted ν_μ flux in anti- ν mode constrained by $< 15\%$



Last word on $\bar{\nu}$ -mode flux

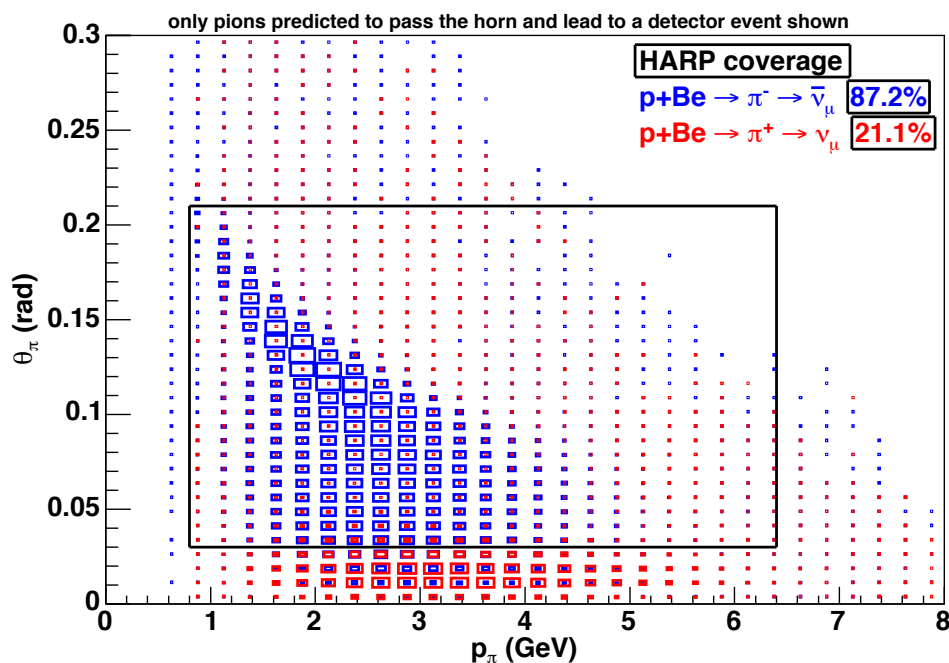
Joe Grange

NuInt 2012

Oct. 25 2012



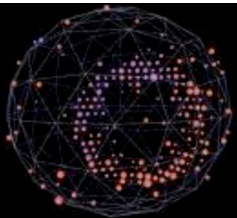
- ▶ Wrong signs constrained to a sub-dominant uncertainty in all anti- ν mode analyses
- ▶ Let's move to anti- ν analyses, where we *can* exploit HARP data



“right sign”
 $\bar{\nu}_\mu$ flux
well-constrained
by HARP data



- I. MiniBooNE and $\bar{\nu}$ -mode beam
 - wrong-sign background
2. **Neutral-current elastic measurement**
 - reconstruction + selection
 - cross-section calculation
 - results
3. Charged-current quasi-elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
4. Combined measurements
5. Summary



(Anti) neutrino-nucleon neutral current elastic (NCE) scattering

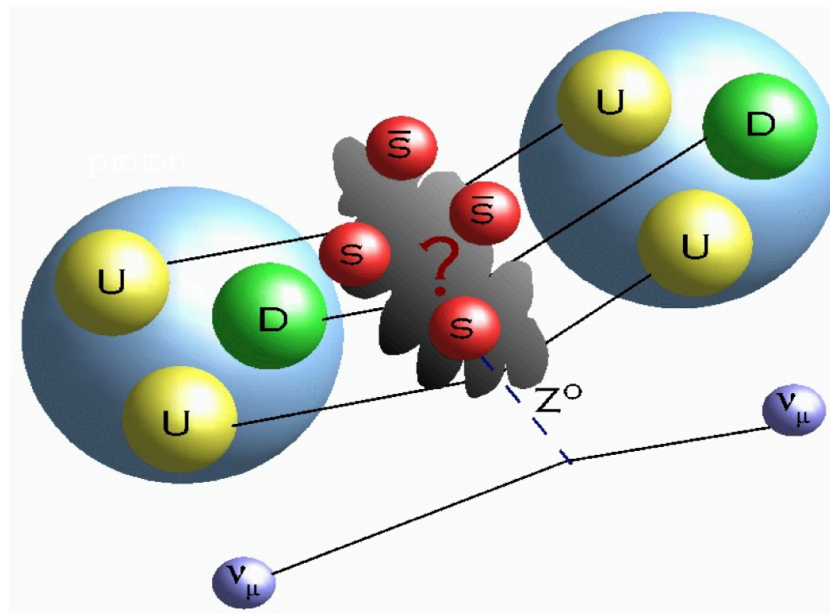
Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Most fundamental neutral current probe of the nucleon
- ▶ Cleanly offers sensitivity to hadronic side of elastic interactions



- ▶ ν_μ NCE analysis

PRD 82, 092005 (2010)



Nucleon reconstruction

Joe Grange

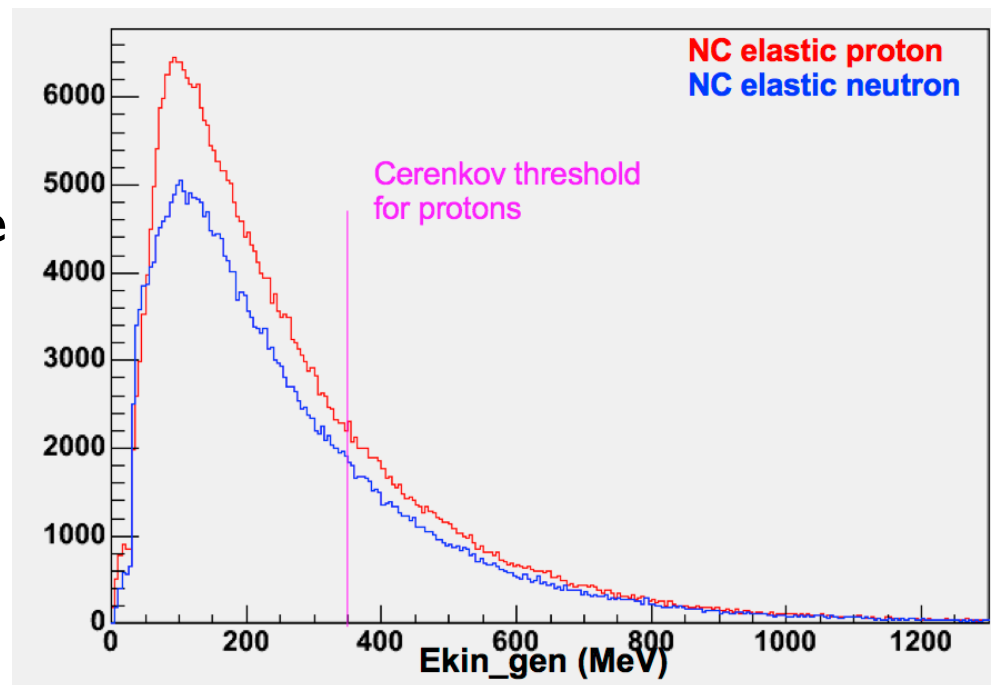
NuInt 2012

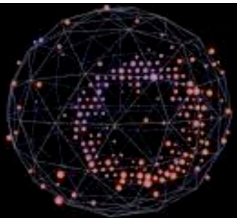
Oct. 25 2012



- ▶ We measure sum of n+p NC interactions: identical isotropic scintillation signature for bulk of spectra
- ▶ Some separation above Cherenkov threshold (350 MeV)

- ▶ Dedicated fitter identifies kinematics via PMT hit charge and time-likelihood maximization
 - assumes outgoing N is proton
 - position res. ~ 0.7 m
 - energy res. $\sim 20\%$





Event selection

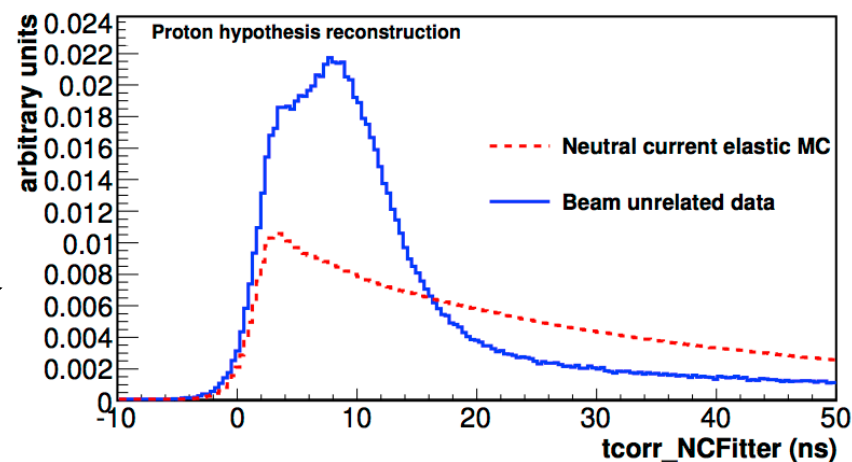
Joe Grange

NuInt 2012

Oct. 25 2012



1. One subevent
 - removes decaying particles (μ , π)
2. In time with ν beam
3. Low veto activity
 - ensures containment, rejects incoming particles
4. Signal PMT hits > 12
 - reconstructible event
5. Cut on time $\ln(L_e/L_p)$
 - rejects beam-unrelated e's
6. Reco. energy < 650 MeV
 - rejects high E backgrounds
7. 5m fiducial volume



Exp't def'n: 0 μ 's, 0 FS π 's, any # of nucleons



NCE sample



Joe Grange

NuInt 2012

Oct. 25 2012

► 61k events pass selection

- 33% efficiency
- 48% purity

Constrained
by wrong-sign
measurements

Dedicated background
measurement

Process	Contribution
$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + N$	48%
All ν_μ	19%
“Dirt”	17%
NC π	14%

Irreducible bkg:
NC π with no final-state π



Dirt background

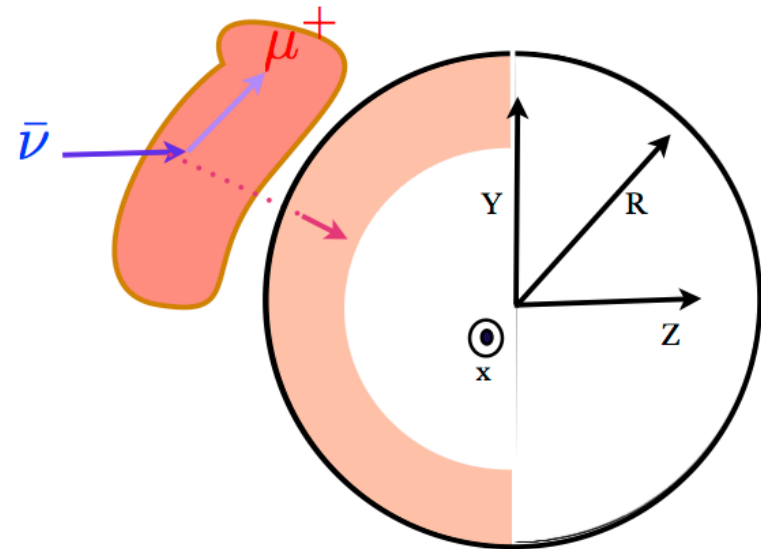
Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ “Dirt”: events produced external to the detector, do not deposit energy in veto, lead to PMT activity
- ▶ Tend to pile up at:
 - high radius
 - upstream half of detector
 - low energy
- ▶ Form dirt-enriched samples based on these correlations
- ▶ Performed in ν -mode NCE measurement as well, need to repeat for $\bar{\nu}$ -mode beam





Dirt background

Joe Grange

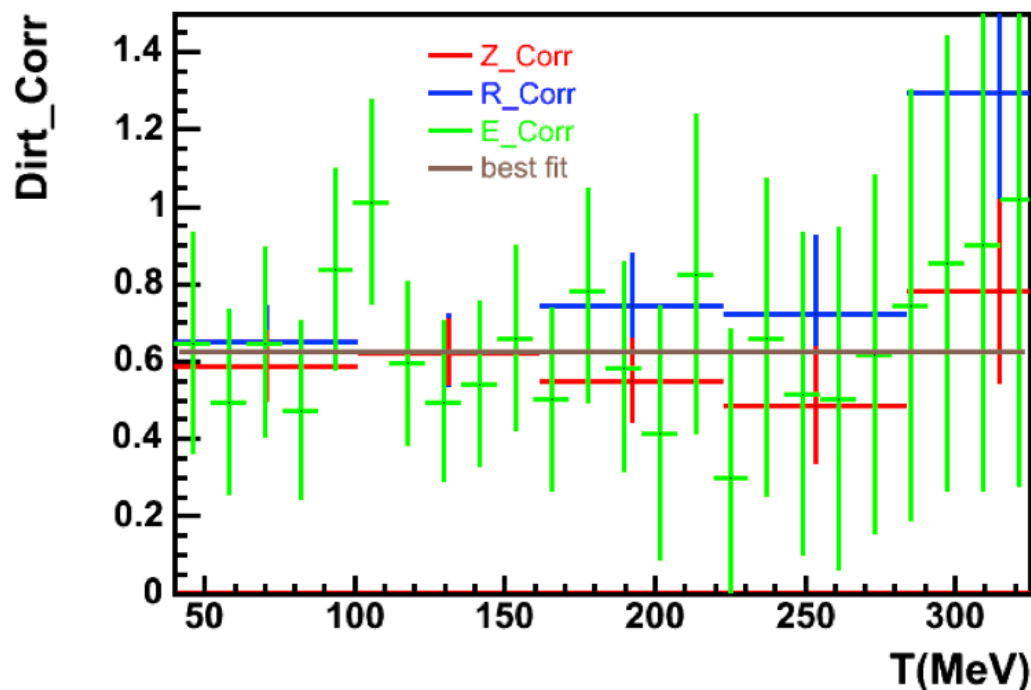
NuInt 2012

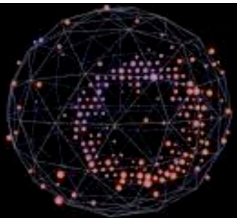
Oct. 25 2012



► Many, many measurements:

- 10 energy bins in the beam direction (**Z_corr**) and radius (**R_corr**)
- fit the energy spectrum directly (**E_corr**)
- Results consistent with v mode NCE dirt fits
- final uncertainty on dirt events **less than 10%**





Irreducible background

Joe Grange

NuInt 2012

Oct. 25 2012



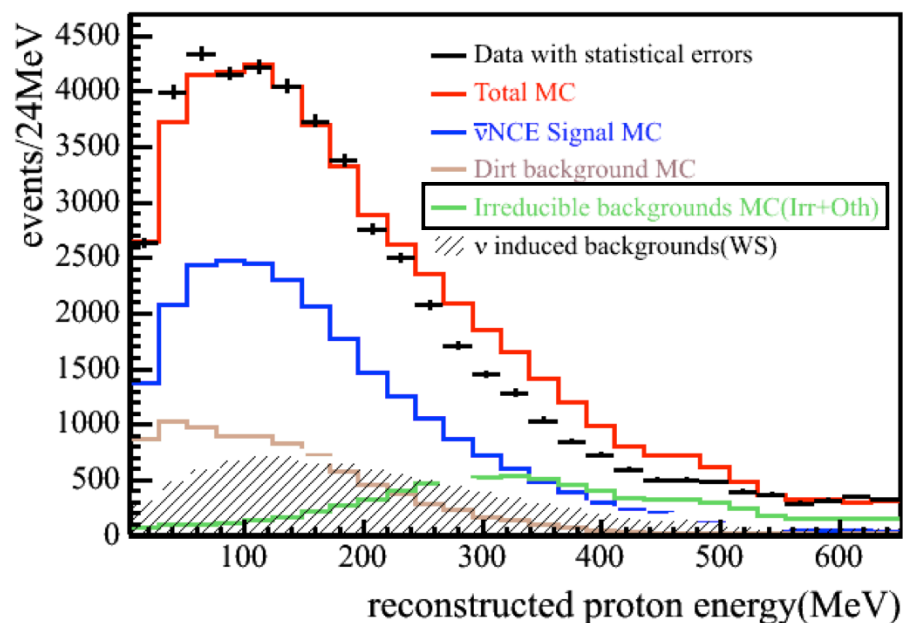
- ▶ Irreducible: $\text{NC}\pi$ with no final-state π , e.g.:
 - $\bar{\nu} p \rightarrow \bar{\nu} p \pi^0$
 - $\bar{\nu} p \rightarrow \bar{\nu} n \pi^+$
 - $\bar{\nu} n \rightarrow \bar{\nu} n \pi^0$
 - $\bar{\nu} n \rightarrow \bar{\nu} p \pi^-$

- ▶ **Rely on MC** to predict this background

- 30 - 40% errors assigned

- ▶ Will also report what was subtracted to allow model-independent comparisons

- following previous MiniBooNE conventions





Cross-section calculation

Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Main result is $d\sigma/dQ^2$. Can calculate Q^2 based on nucleon energy **assuming** interaction with an independent, at-rest target

$$Q^2 = 2m_N \sum T_N$$

- ▶ Notice! Reconstructed solely on **hadronic** activity, CCQE Q^2 reconstructed solely on **leptonic** activity

- ▶ Simple σ calculation from here:

$$\frac{d\sigma}{dQ^2} = \frac{\sum_j U_{ij} (d_j \times \frac{s_j}{s_j + b_j})}{\Delta Q^2 \epsilon_i \Phi T}$$

Diagram illustrating the components of the cross-section calculation formula:

- U_{ij} : unfolding matrix
- d_j : reco data
- s_j : MC signal
- b_j : bkg
- ΔQ^2 : bin width
- ϵ_i : detection efficiency
- Φ : int. flux
- T : nucleon targets



Systematic uncertainties



Joe Grange

NuInt 2012

Oct. 25 2012

- ▶ Most uncertainties on parameters, processes that affect the final measurement evaluated through “many universe” MC method:

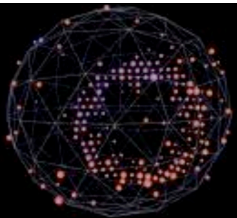
$$\frac{d\sigma^k}{dQ^2} = \frac{\sum_j U_{ij}^k (d_j \times \frac{s_j^k}{s_j^k + b_j^k})}{\Delta Q^2 \epsilon_i^k \Phi^k T}$$

k: parameter/process excursion from “best-guess”

- ▶ Difference of these alternate σ 's from central-value sets systematic uncertainty

Error source	Normalization uncertainty (%)
anti-v flux	6
Backgrounds	6
Detector	15
Unfolding	7
Total (includes correlations)	21

Uncertainty dominated
by light propagation
model



Results

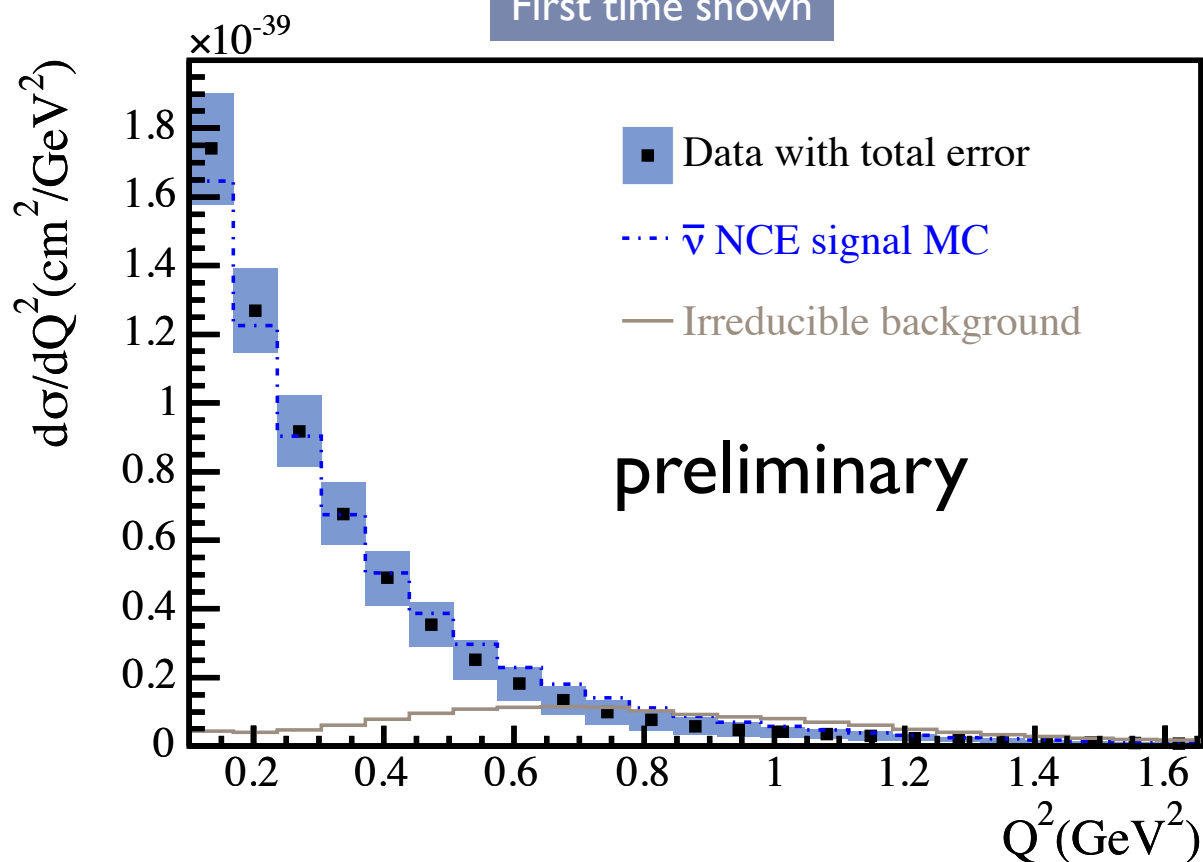
Joe Grange

NuInt 2012

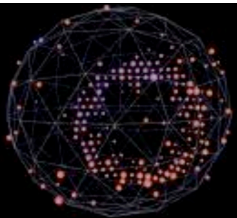
Oct. 25 2012



First time shown



- Adequate agreement with MC prediction tuned to ν_μ CCQE data

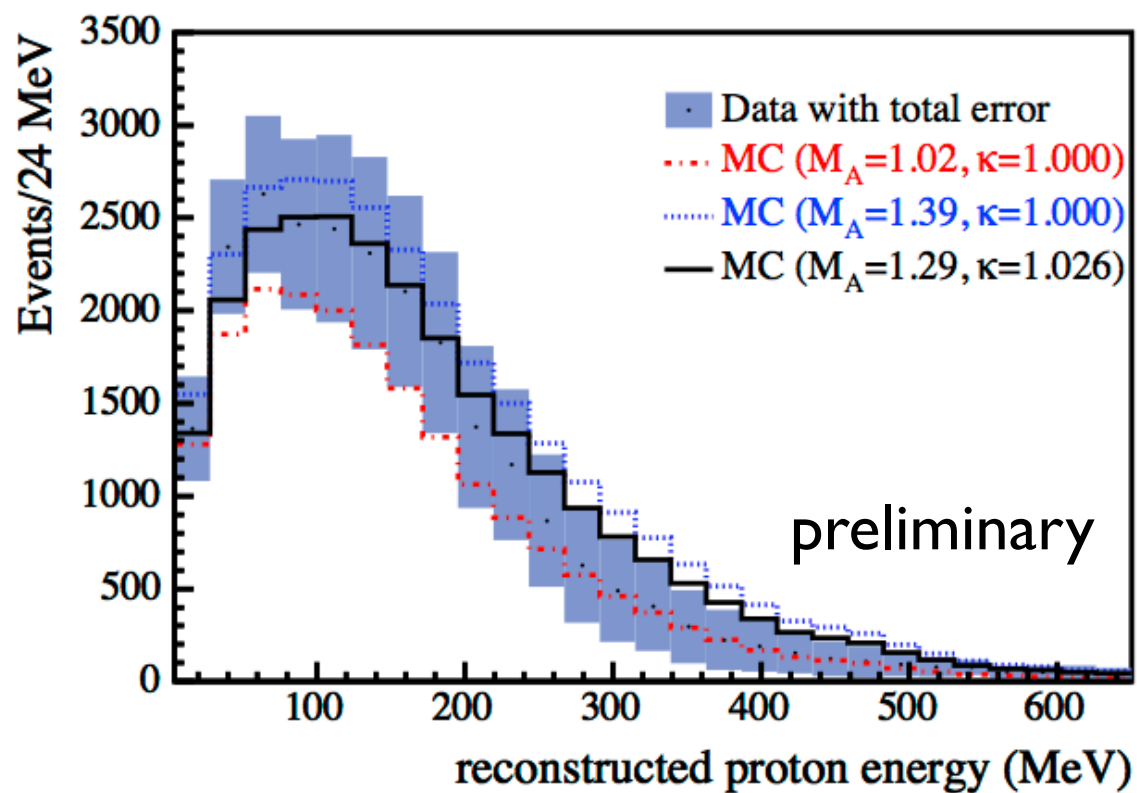


More model comparisons

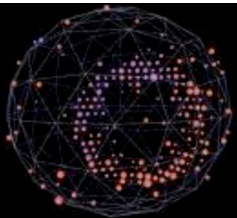
Joe Grange

NuInt 2012

Oct. 25 2012



- Not much shape sensitivity to model parameters



1. MiniBooNE and $\bar{\nu}$ -mode beam
 - wrong-sign background
2. Neutral-current elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
3. Charged-current quasi-elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
4. Combined measurements
5. Summary



$\bar{\nu}_\mu$ CCQE

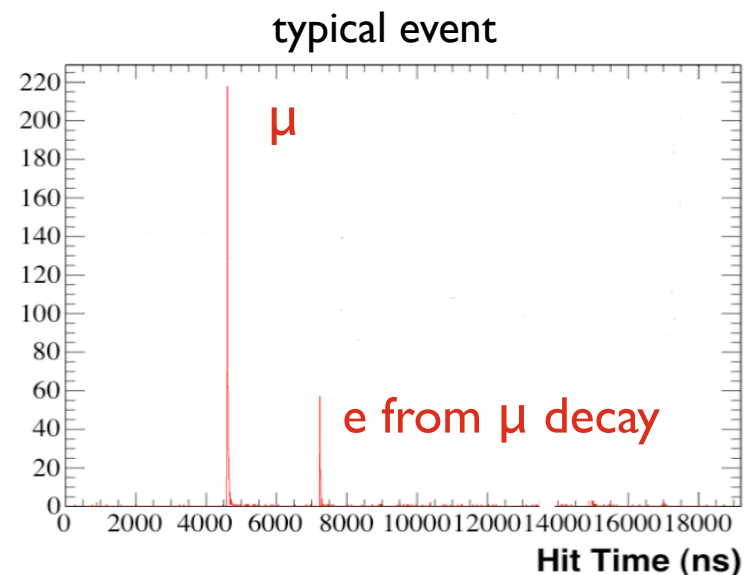
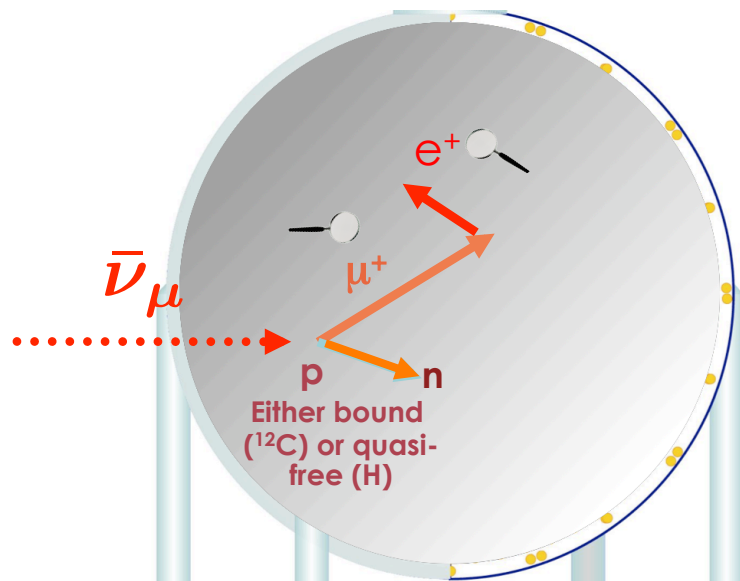
Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Complementary to the NCE analysis with exclusive hadronic reconstruction, MiniBooNE CCQE is based **exclusively** on μ kinematics (no attempt to recover hadronic activity)
- ▶ $\bar{\nu}_\mu$ CCQE only involves protons: MiniBooNE medium CH_2 , so sample is mix of bound and free scattering





$\bar{\nu}_\mu$ CCQE reconstruction

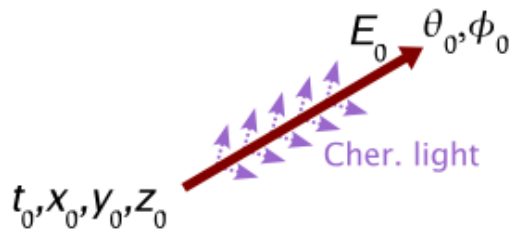
Joe Grange

NuInt 2012

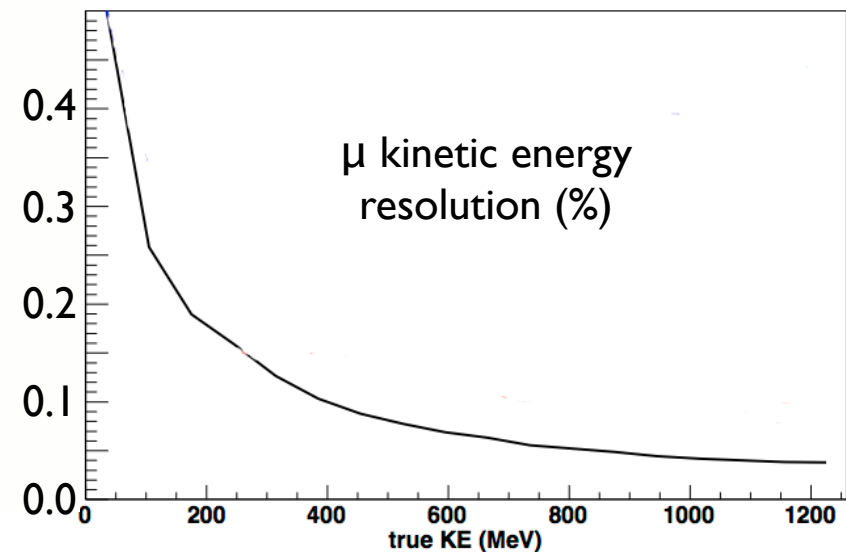
Oct. 25 2012



- ▶ Similar to proton NCE fitter, μ kinematics identified by fitting PMT hit topology and timing



- ▶ μ 's leave distinctive Cherenkov ring, reconstruction performs well



NIM A608, 206 (2009)

- ▶ This motivates exploitation of our large statistics to map the σ as a function of μ kinematics: **main result** $d^2\sigma/dT_\mu d(\cos\theta_\mu)$



$\bar{\nu}_\mu$ CCQE selection

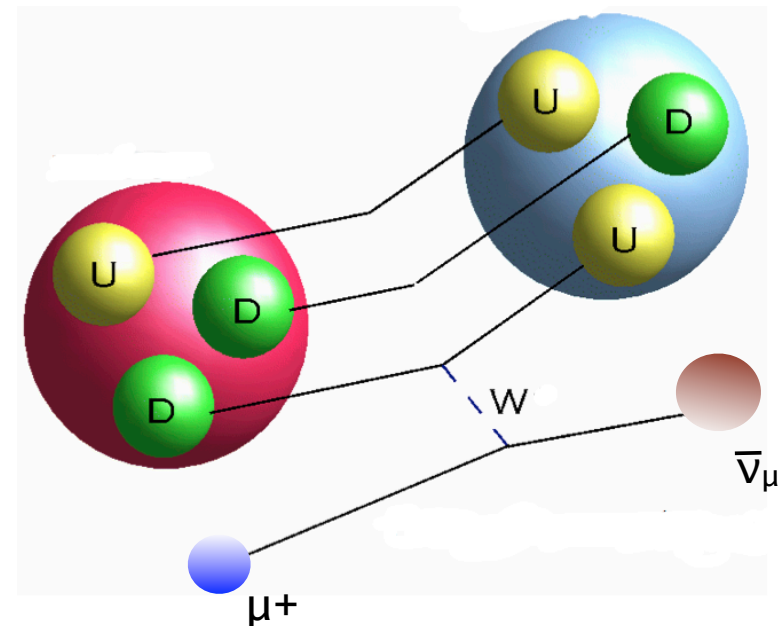
Joe Grange

NuInt 2012

Oct. 25 2012



1. Two subevents
 - consistent with prompt μ + decay e
2. In time with ν beam
3. $T_\mu > 200$ MeV
 - removes beam-unrelated e 's
4. 2nd subevent vertex consistent decay of prompt particle
 - based on observed μ kinematics
5. μ/e separation PID
 - single-pion bkg's look more e-like
6. 5m fiducial volume
7. Low veto activity
 - containment + nothing coming in



Identical selection to ν_μ CCQE analysis:
single μ , 0 π , any # nucleons



$\bar{\nu}_\mu$ sample composition

Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ **70k** events: 60% $\bar{\nu}_\mu$ CCQE purity

- 43% ^{12}C events, 17% H_2

- ▶ 30% efficiency

- ▶ Largest background: ν_μ CCQE

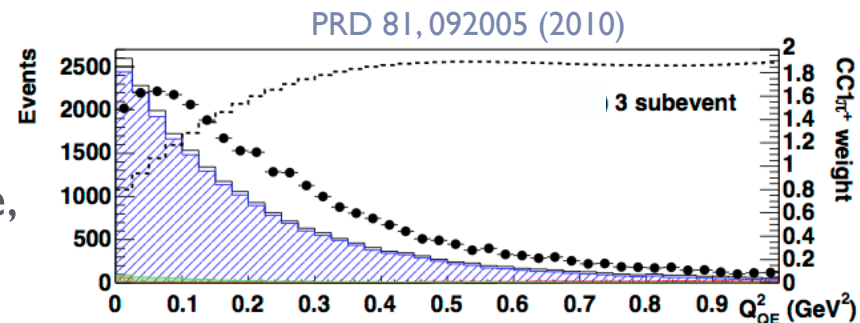
- measured!

- ▶ Next largest: $\text{CC}\pi^-$ (next)

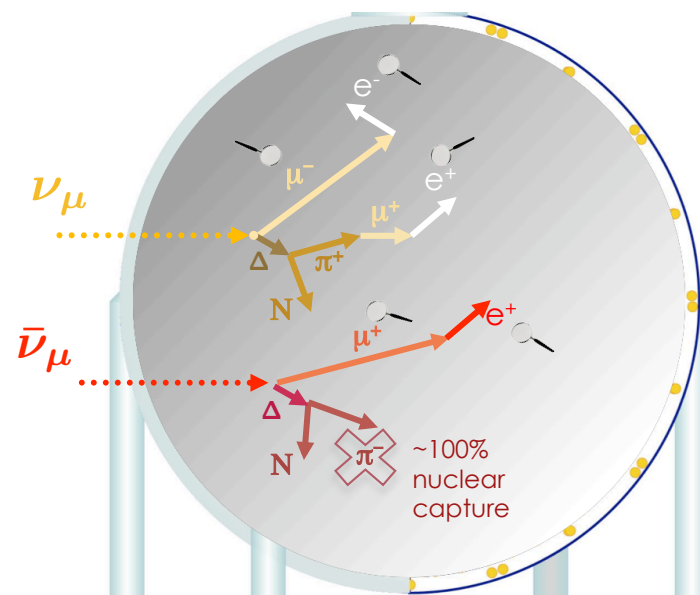
Interaction channel	Contribution (%)
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (bound p)	43.2
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (quasi-free p)	17.1
$\nu_\mu + n \rightarrow \mu^- + p$	16.6
$\bar{\nu}_\mu + N \rightarrow \mu^+ + N + \pi^-$ (resonant)	10.4
$\nu_\mu + N \rightarrow \mu^- + N + \pi^+$ (resonant)	3.8
$\bar{\nu}_\mu + A \rightarrow \mu^+ + A + \pi^-$ (coherent)	3.3
$\bar{\nu}_\mu + N \rightarrow \mu^+ + N + \pi^0$	2.8
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$	
$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^-$	2.0
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$	
Others	0.7

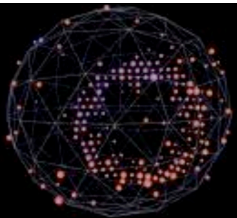


- ▶ Single- π bkg for ν_μ CCQE analysis:
ID'd CC π^+ events using 2-Michel tag
- empirically constrained their rate + shape,
apply to bkg prediction

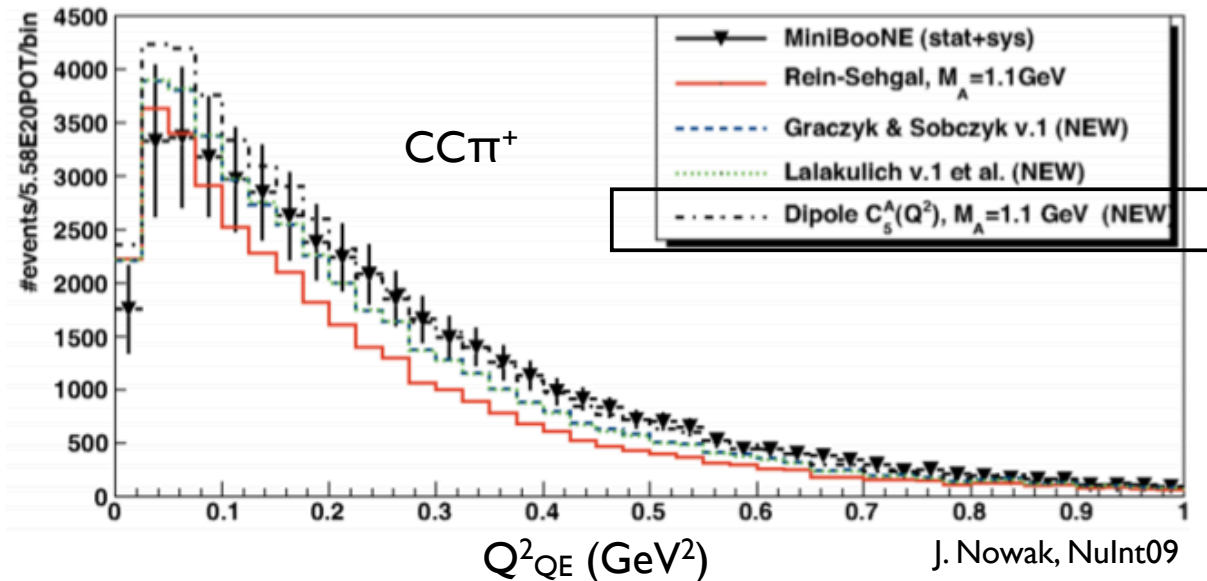


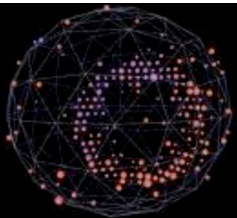
- ▶ Not possible in anti- ν mode: single-pion mechanism CC π^- , stopped π^- absorbed in medium $\sim 100\%$, 2nd Michel not produced



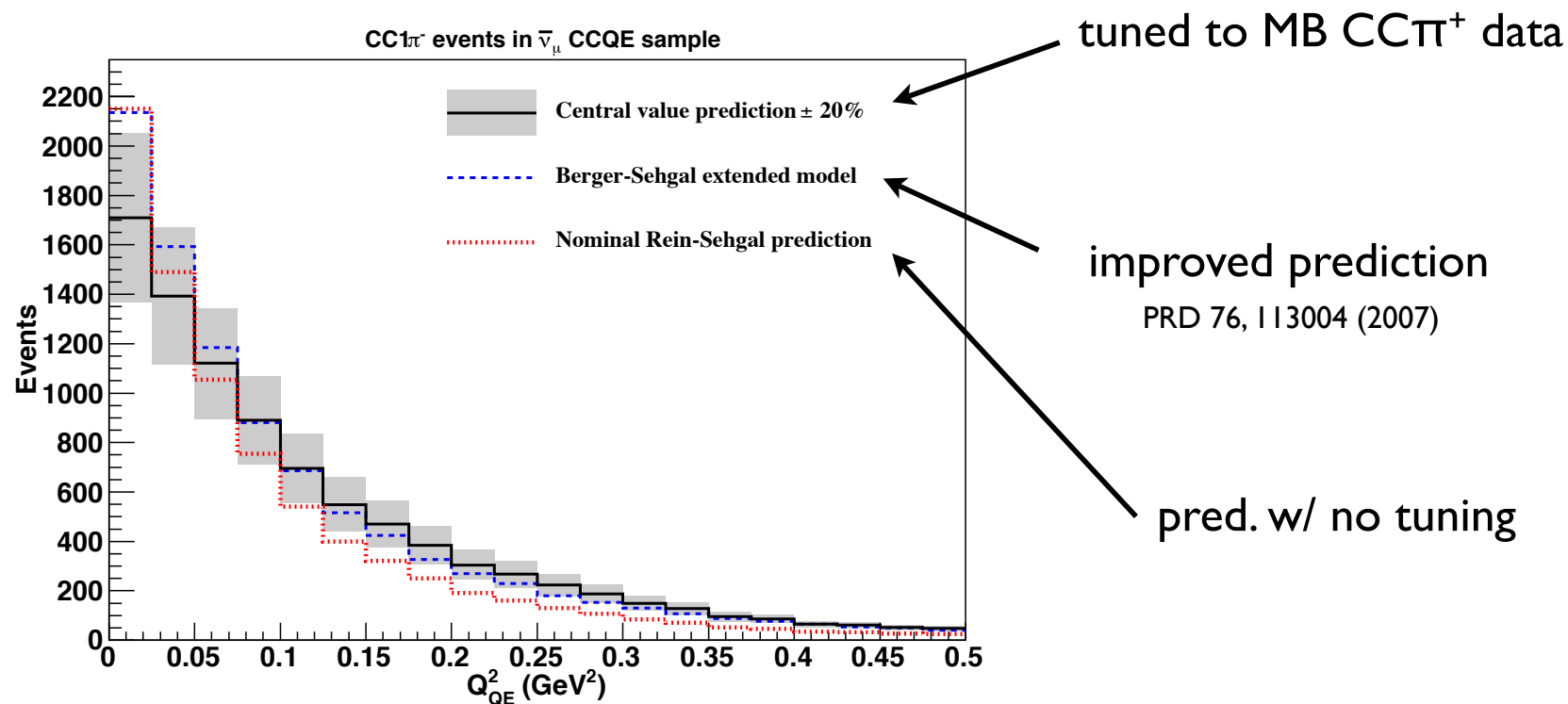


- ▶ Apply the same constraint measured in CC π^+ sample to CC π^- events
 - uncertain extrapolation!
- ▶ Can do better: use improved π -production model that agrees with MB CC π^+ data as cross-check
 - improvements include muon mass effects (absent in Rein-Sehgal)





► Comparison to MiniBooNE predictions



► Level of agreement suggests 20% uncertainty is sufficient



Cross-section calculation, uncertainties

Joe Grange

NuInt 2012

Oct. 25 2012



- Calculation identical to ν_μ CCQE σ analysis

$$\frac{d^2\sigma}{dT_\mu d(\cos\theta_\mu)} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Delta T_\mu \Delta(\cos\theta_\mu) \epsilon_i \Phi T}$$

Diagram illustrating the components of the cross-section calculation formula:

- U_{ij} : unfolding matrix
- d_j : reco data
- b_j : reco bkg
- ΔT_μ : bin widths
- $\Delta(\cos\theta_\mu)$: detection efficiency
- ϵ_i : int. flux
- ΦT : nucleon targets

- Same procedure to eval. measurement uncertainties as NCE



Uncertainty summary



Joe Grange

NuInt 2012

Oct. 25 2012

► **Leading uncertainties:**

- flux: roughly due in equal parts to HARP π^- data, beam modeling
- backgrounds, roughly split between wrong sign CCQE & $\text{CC}\pi^-$ production

Error source	Normalization uncertainty (%)
anti- ν flux	9
Backgrounds	9
Detector	5
Unfolding	2
Total (includes correlations)	14



Results: double-differential on CH_2

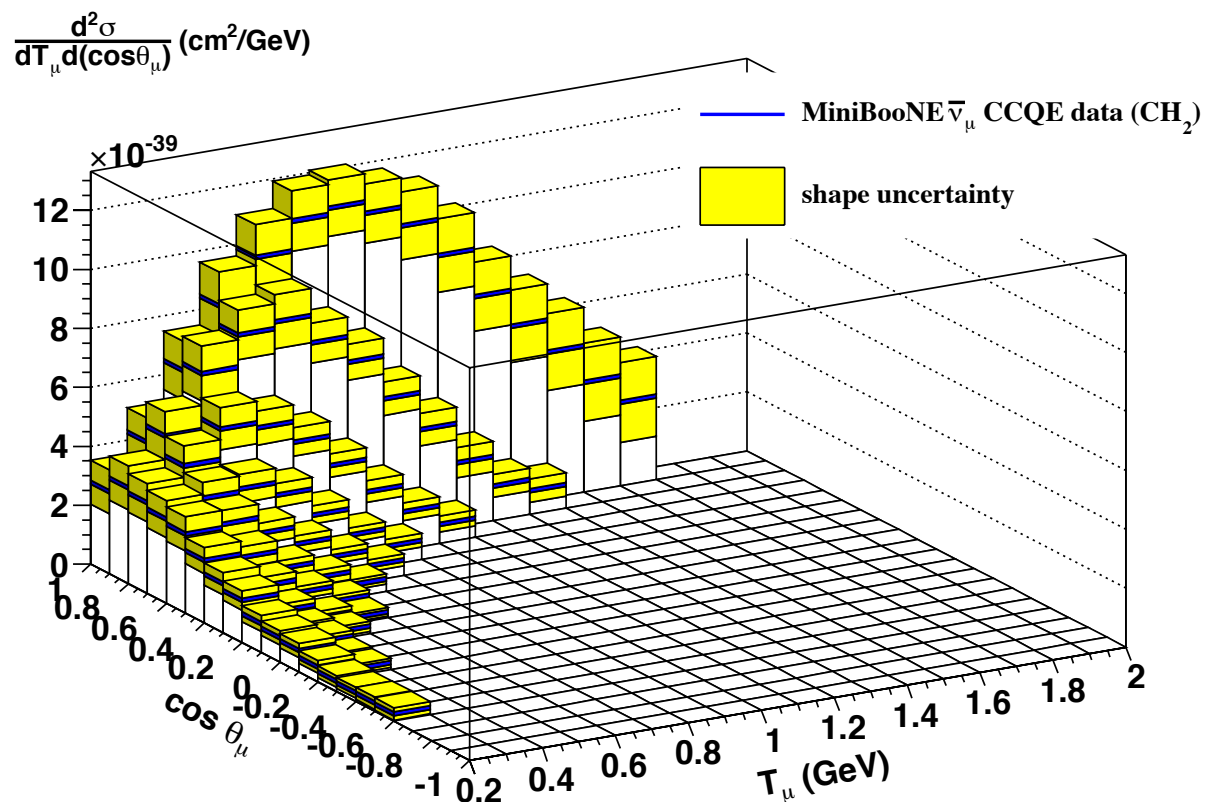
Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Least model-dependent measurement possible with MiniBooNE data.
Independent of CCQE interaction assumptions



First time
shown



Results: double-differential on CH_2

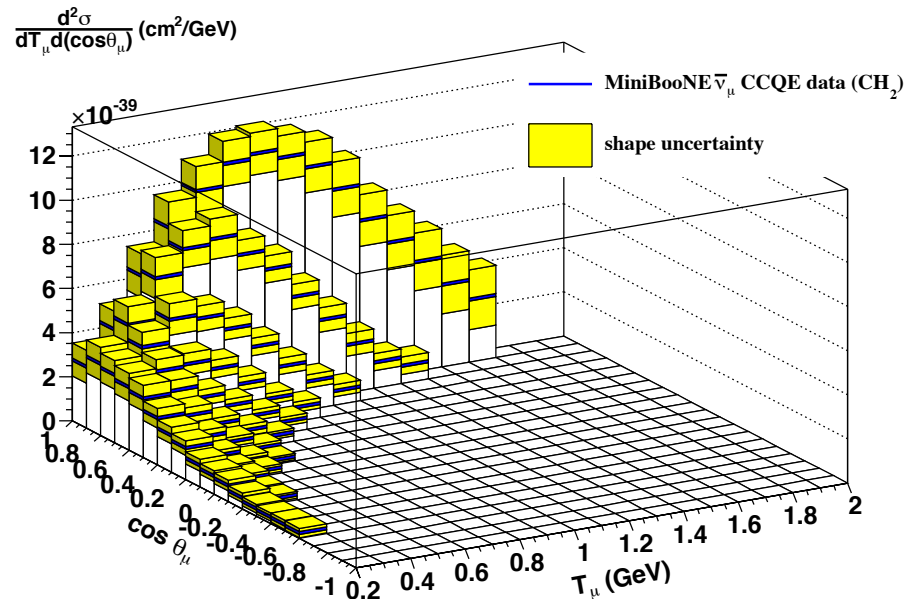
Joe Grange

NuInt 2012

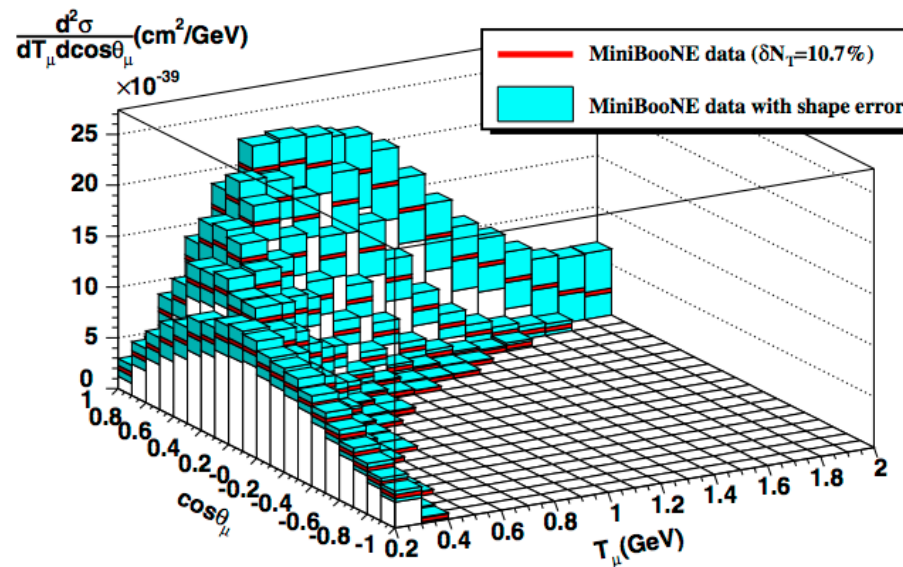
Oct. 25 2012



- ▶ $\bar{\nu}_\mu$ CCQE much more forward-going compared to ν_μ



$\bar{\nu}_\mu$ CCQE



ν_μ CCQE



$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only

Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ To facilitate comparisons with theoretical calculations, CCQE on hydrogen subtracted to form ^{12}C -only σ (using L-S $M_A = 1.02 \pm 0.02$ GeV)
 - introduces model dependence, also larger errors due to lower sample purity



$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only

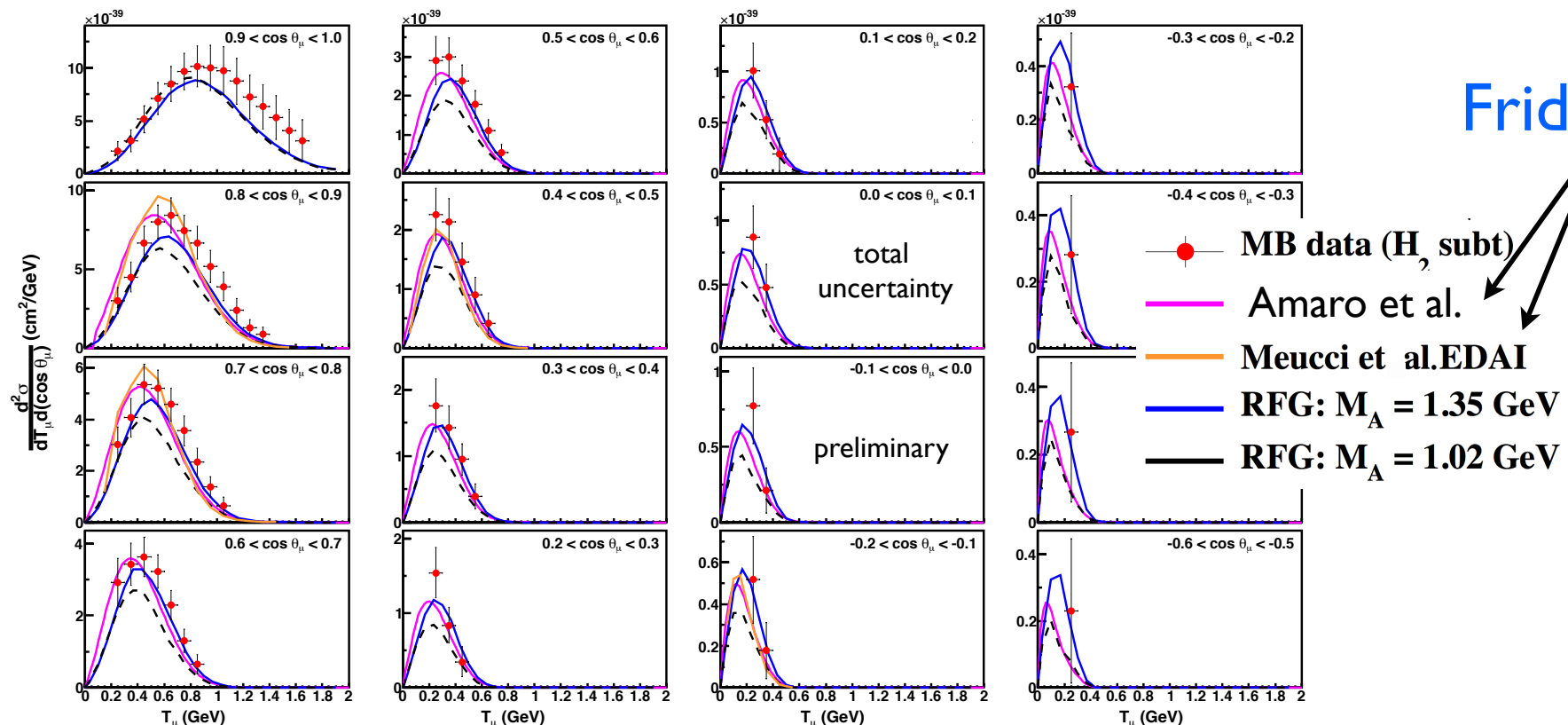
Joe Grange

NuInt 2012

Oct. 25 2012



- To facilitate comparisons with theoretical calculations, CCQE on hydrogen subtracted to form ^{12}C -only σ (using $L\text{-}S\ M_A = 1.02 \pm 0.02\ \text{GeV}$)
 - introduces model dependence, also larger errors due to lower sample purity





$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only

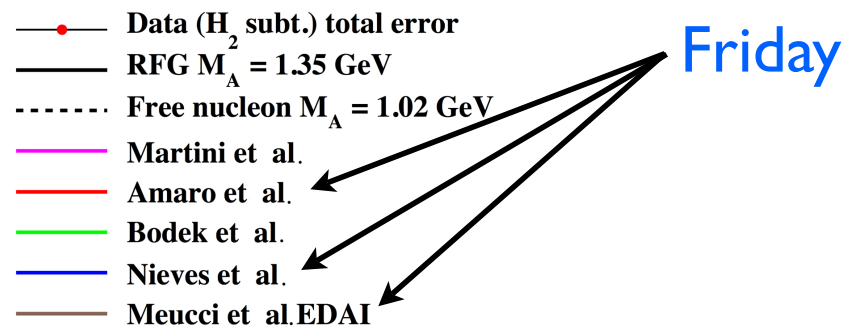
Joe Grange

NuInt 2012

Oct. 25 2012



- Further model comparisons: assuming underlying interaction is with **independent, at-rest nucleon**, can recover incident anti- ν energy, unfold to generated energy



$$E_{\bar{\nu}}^{\text{QE}} = \frac{2(M_p - E_B)E_\mu - (E_B^2 - 2M_p E_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos \theta_\mu]}$$



$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only

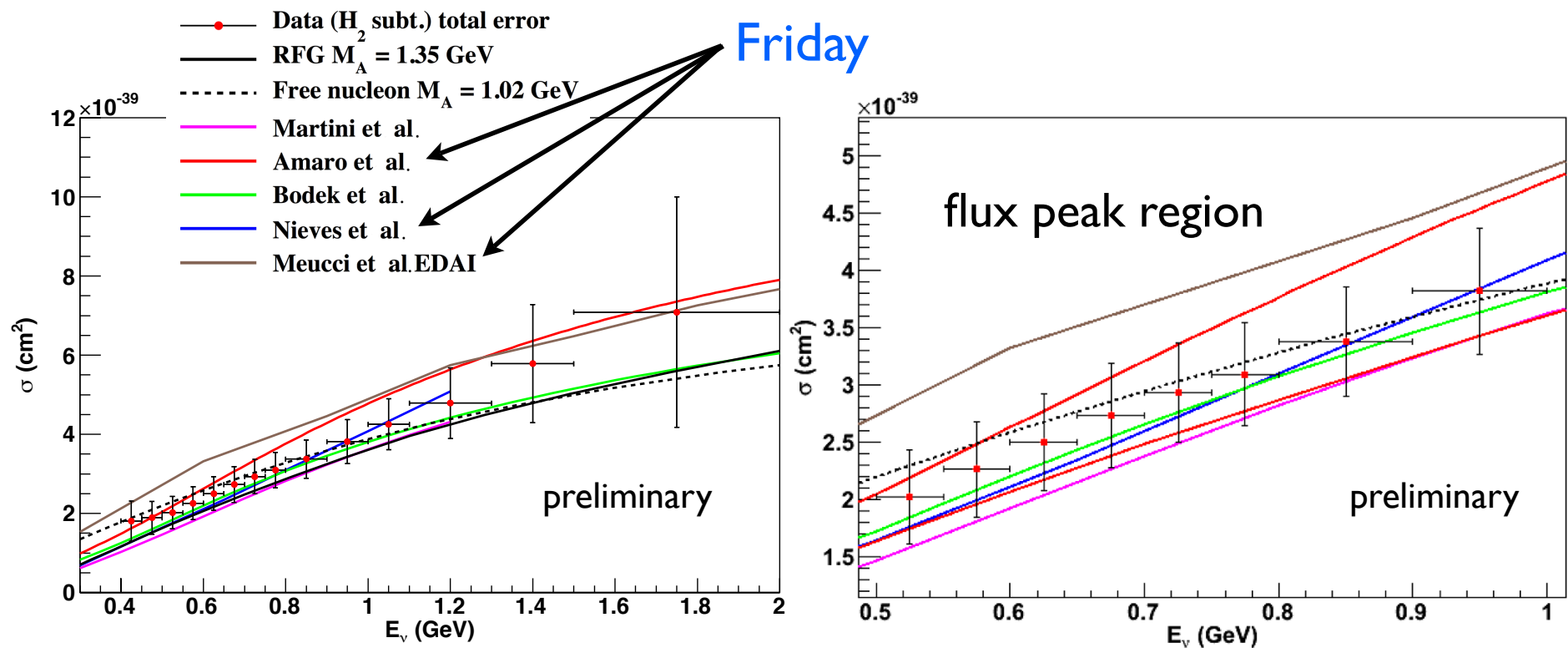
Joe Grange

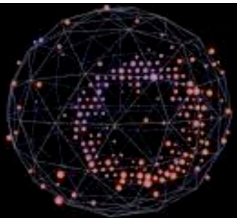
NuInt 2012

Oct. 25 2012



- Further model comparisons: assuming underlying interaction is with **independent, at-rest nucleon**, can recover incident anti- ν energy, unfold to generated energy





1. MiniBooNE and $\bar{\nu}$ -mode beam
 - wrong-sign background
2. Neutral-current elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
3. Charged-current quasi-elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
4. **Combined measurements**
5. Summary



BooNE of data!



Joe Grange

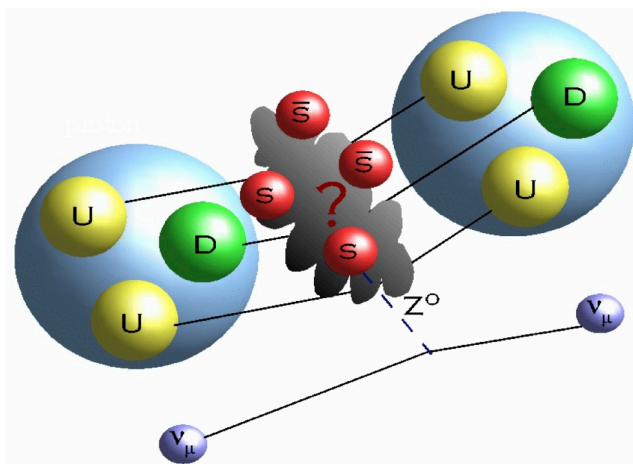
NuInt 2012

Oct. 25 2012

► Robust MiniBooNE measurements:

ν_μ NCE

PRD 82, 092005 (2010)

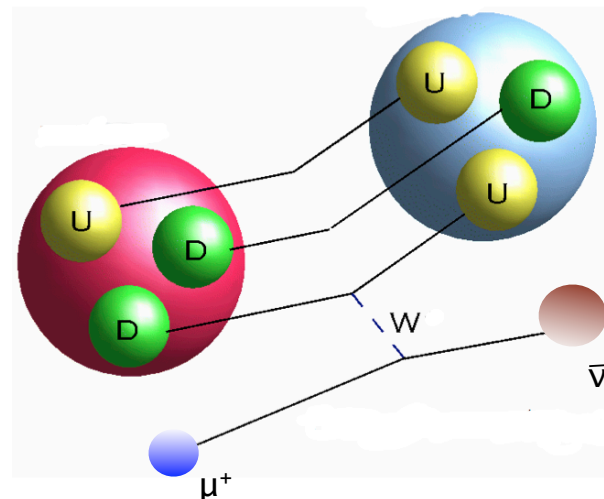


$\bar{\nu}_\mu$ NCE

This work

ν_μ CCQE

PRD 81, 092005 (2010)



$\bar{\nu}_\mu$ CCQE

This work

► Can exploit correlated systematics:

- detector errors: anti- ν_μ / ν_μ , same channel
- flux errors: NCE/CCQE in same beam

} will show combined measurements of both types



NCE ratio: $\bar{\nu}_\mu / \nu_\mu$

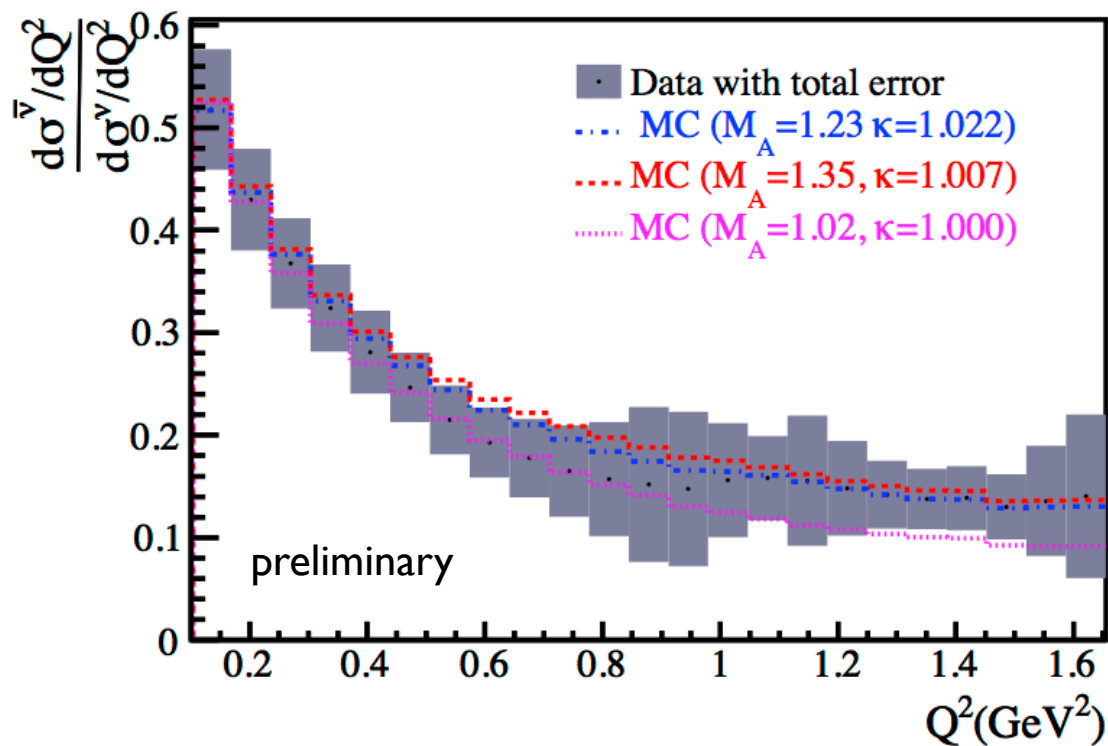
Joe Grange

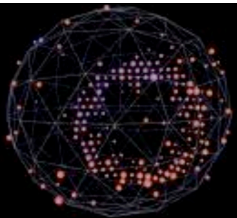
NuInt 2012

Oct. 25 2012



- Carefully evaluated correlated uncertainties implemented
 - biggest gain in light propagation model





CCQE: $\nu_\mu / \bar{\nu}_\mu$

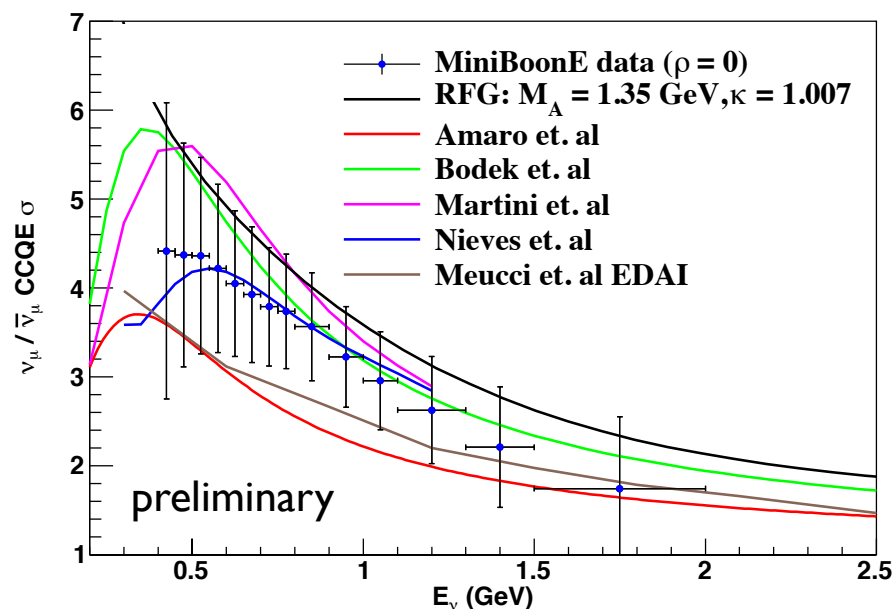
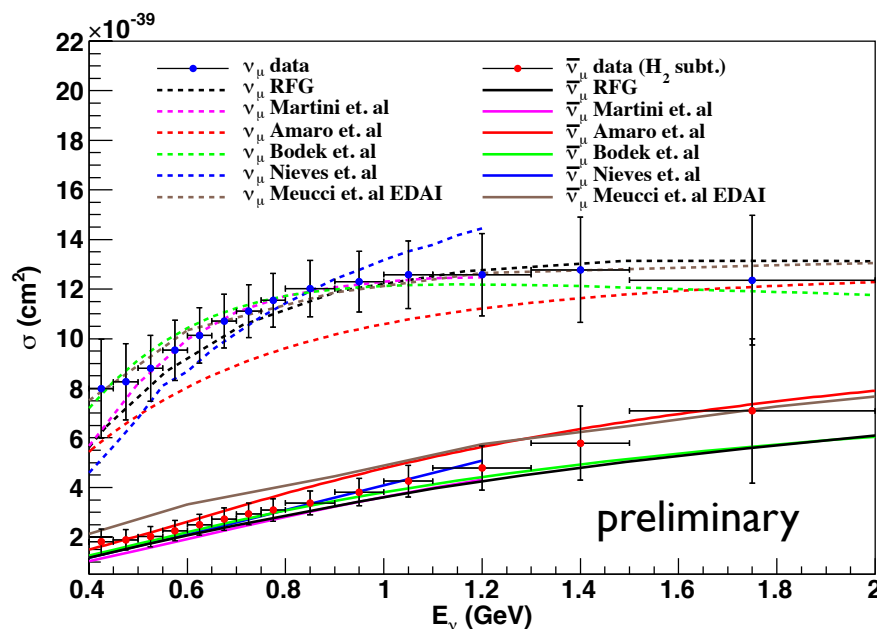
Joe Grange

NuInt 2012

Oct. 25 2012



- Correlations not yet evaluated
 - ratio measurement will only get better





CCQE: $\nu_\mu / \bar{\nu}_\mu$

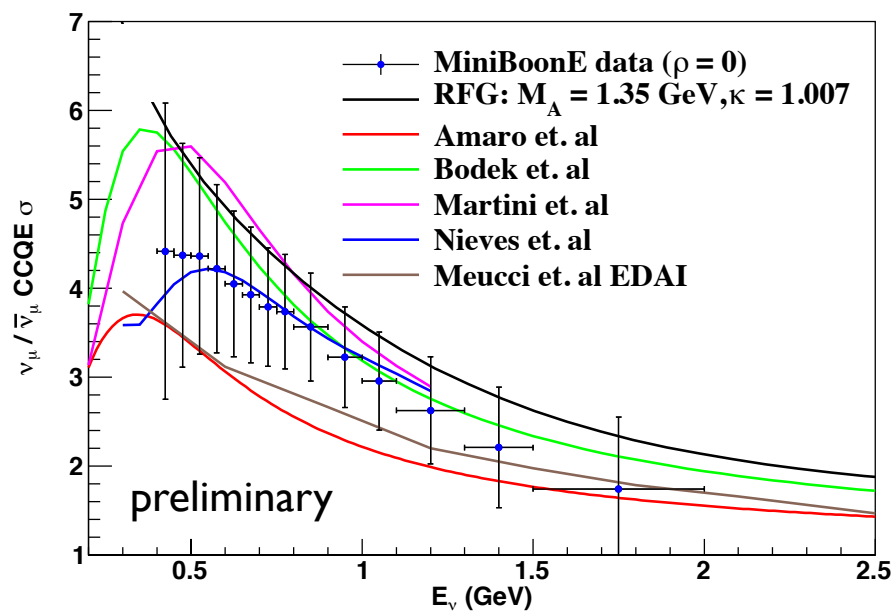
Joe Grange

NuInt 2012

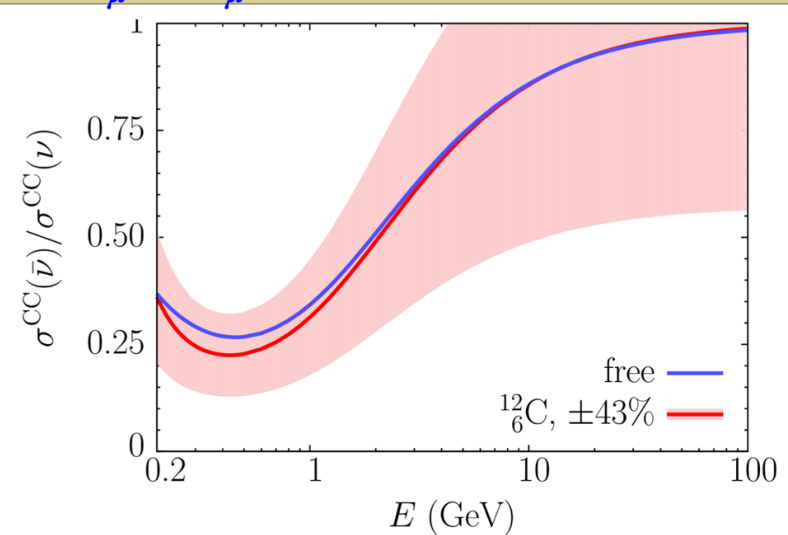
Oct. 25 2012



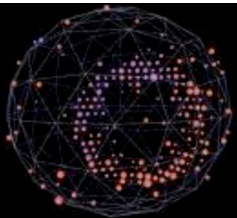
- (Inverted) comparison to earlier prediction



$\bar{\nu}_\mu$ to ν_μ cross sections ratio



A. Ankowski talk



CCQE: $\nu_\mu - \bar{\nu}_\mu$

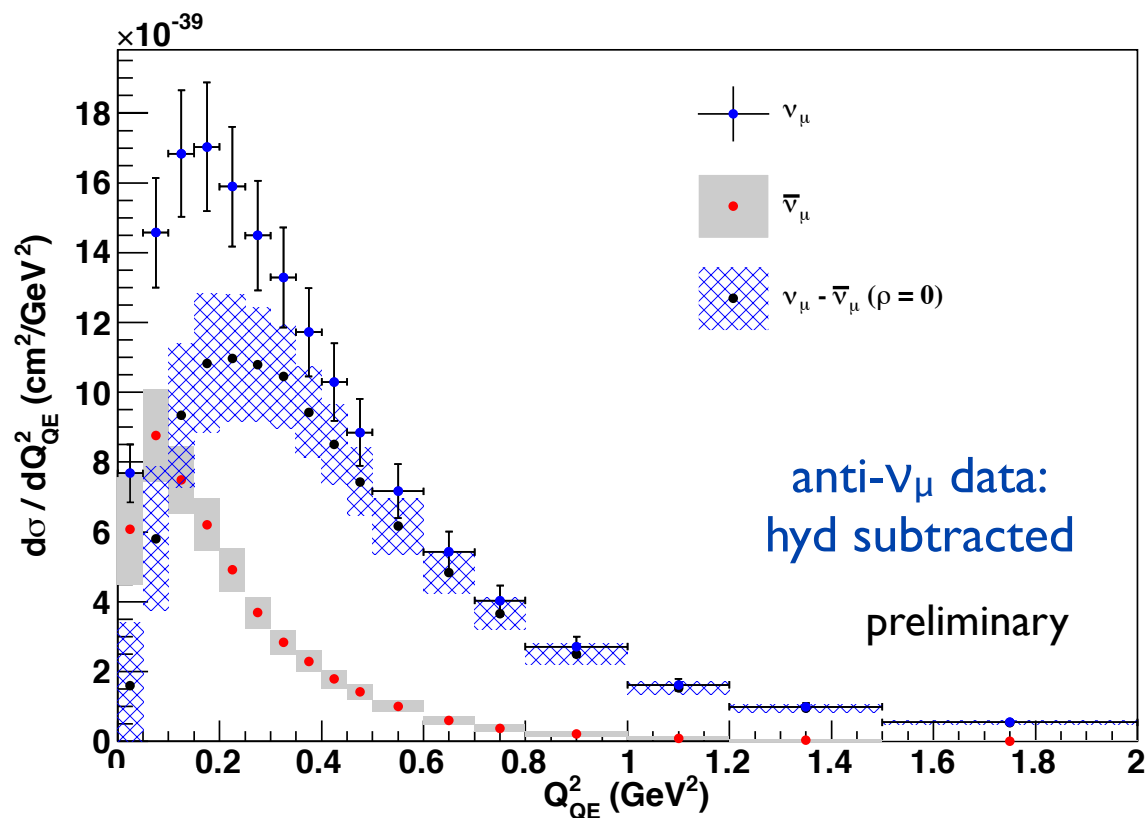
Joe Grange

NuInt 2012

Oct. 25 2012



- Difference as a function of Q_2^{QE}
 - again, correlations not yet taken into account





NCE/CCQE ratio for $\nu_\mu, \bar{\nu}_\mu$

Joe Grange

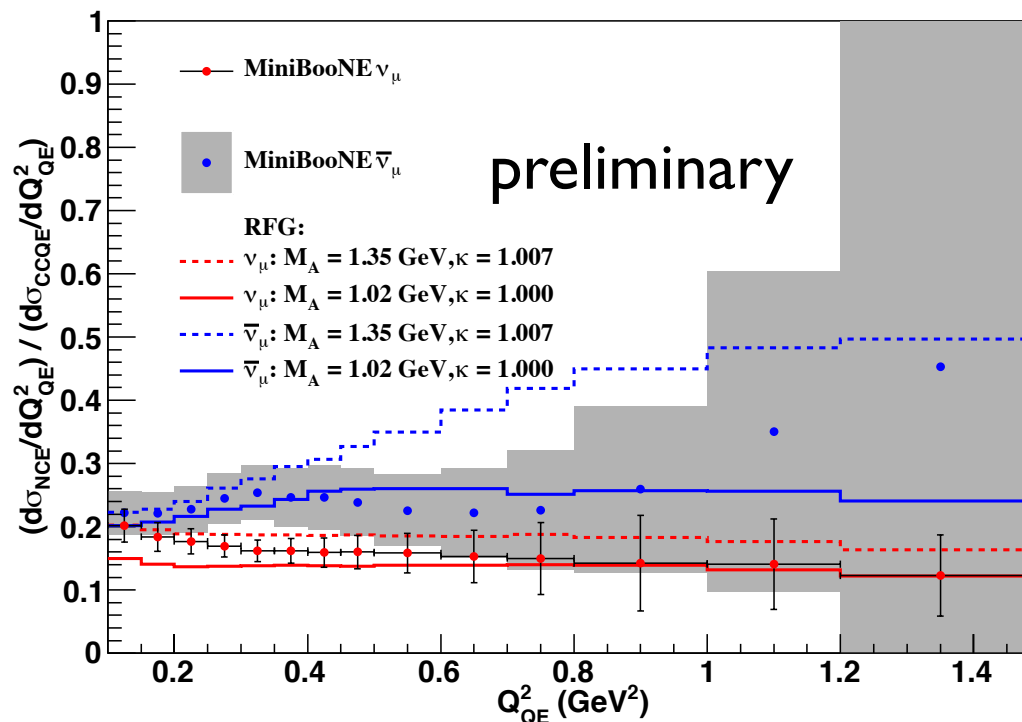
NuInt 2012

Oct. 25 2012



- Recall exp't definitions of Q_{QE}^2 very different here: **hadronic** vs. **leptonic** observations

$$Q_{QE,NCE}^2 = 2m_N \sum T_N \quad Q_{QE,CCQE}^2 = 2E_\nu^{QE} (p_\mu \cos \theta_\mu - m_\mu) + m_\mu^2$$



ν_μ ratio:
PRD 82,
092005 (2010)



NCE/CCQE ratio for $\nu_\mu, \bar{\nu}_\mu$

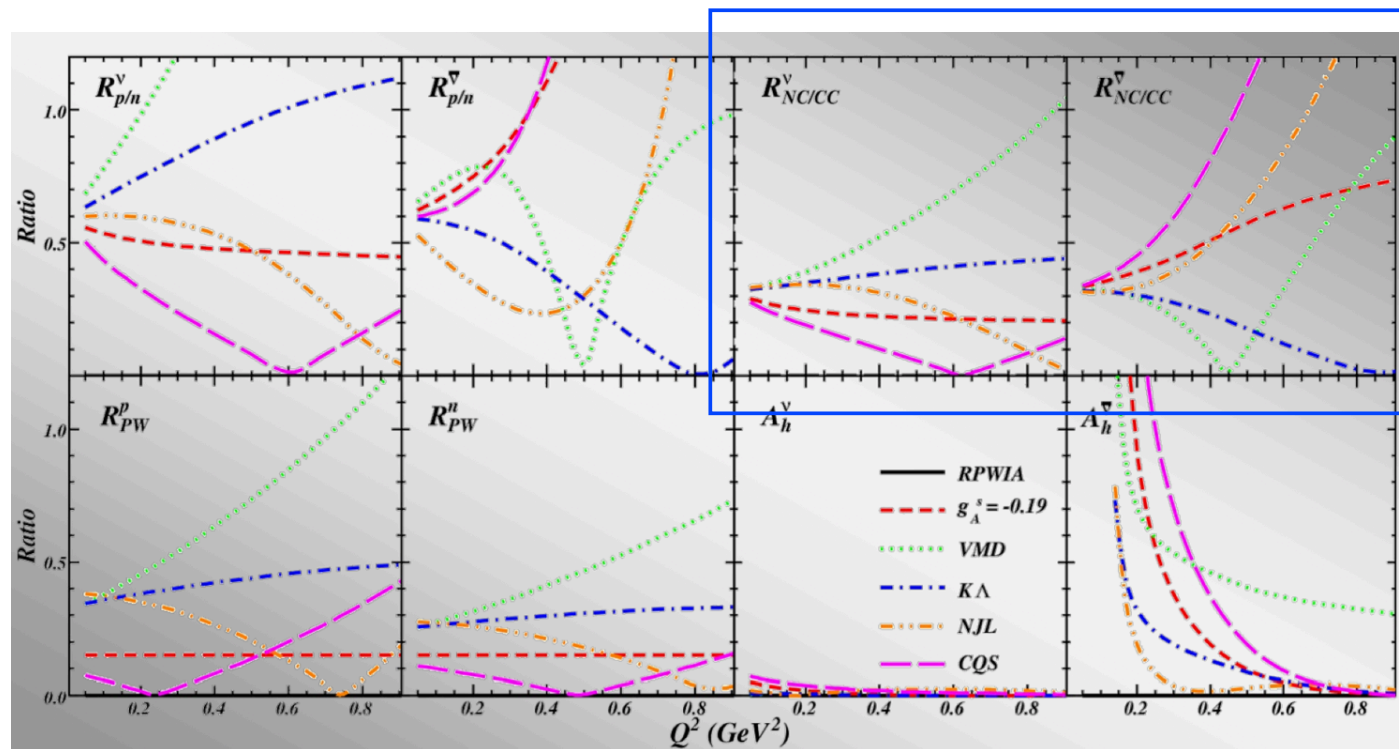
Joe Grange

NuInt 2012

Oct. 25 2012



► Another on-the-fly comparison



N. Jachowicz talk



1. MiniBooNE and $\bar{\nu}$ -mode beam
 - wrong-sign background
2. Neutral-current elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
3. Charged-current quasi-elastic measurement
 - reconstruction + selection
 - cross-section calculation
 - results
4. Combined measurements
5. Summary



Summary



Joe Grange

NuInt 2012

Oct. 25 2012

- ▶ MiniBooNE has analyzed $> 90\%$ of neutrino mode data, and today's analysis brings the total in anti-neutrino mode to $> 80\%$
- ▶ New anti-neutrino CCQE data favor high normalization and harder momentum transfer spectrum compared to expectation associated with $M_A = 1.0$ GeV. NCE data favors higher normalization.
- ▶ Papers from both analyses forthcoming



Summary



Joe Grange

NuInt 2012

Oct. 25 2012

- ▶ MiniBooNE has analyzed $> 90\%$ of neutrino mode data, and today's analysis brings the total in anti-neutrino mode to $> 80\%$

- ▶ New anti-neutrino momentum transfer with $M_A = 1.0 \text{ GeV}$

- ▶ Papers from both

Thanks for your attention!



on and harder
ion associated
ation.



Backup



Joe Grange

NuInt 2012

Oct. 25 2012

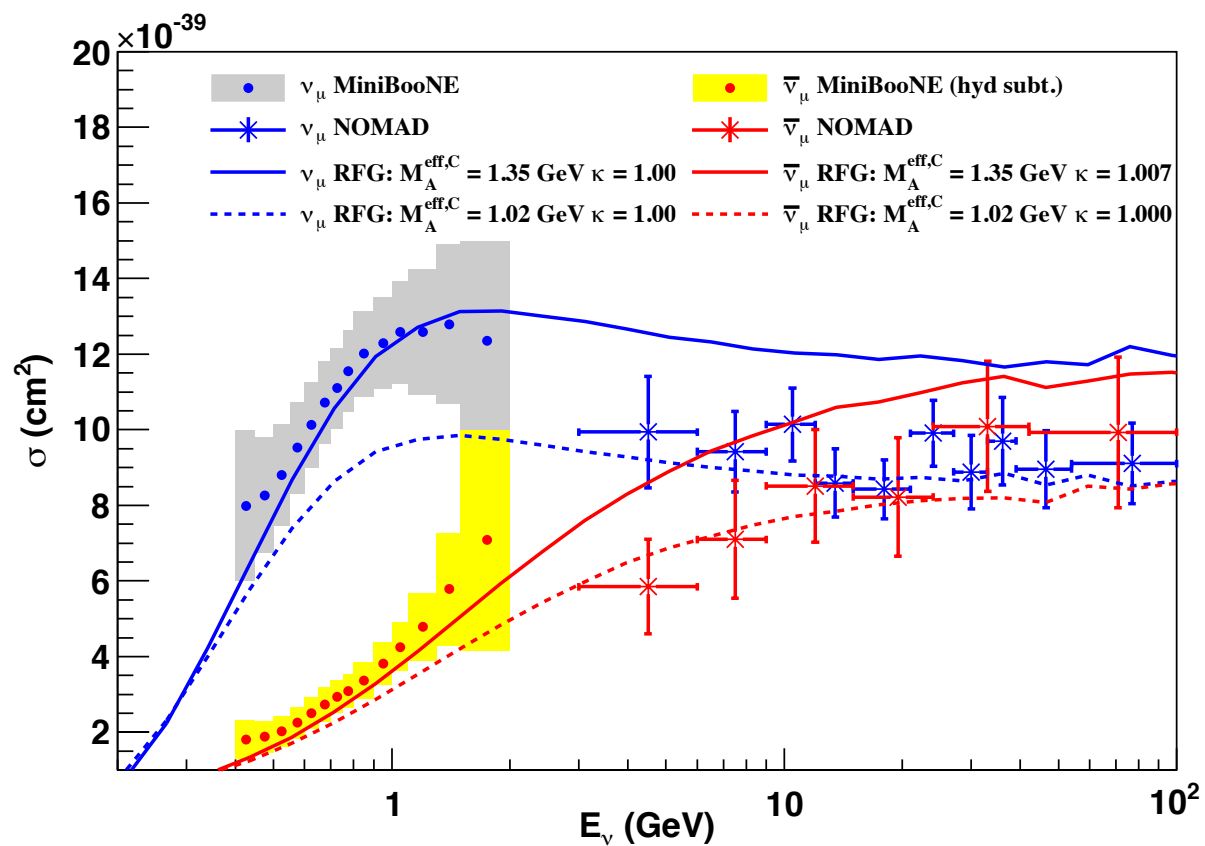


Comparison to NOMAD data

Joe Grange

NuInt 2012

Oct. 25 2012





$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only

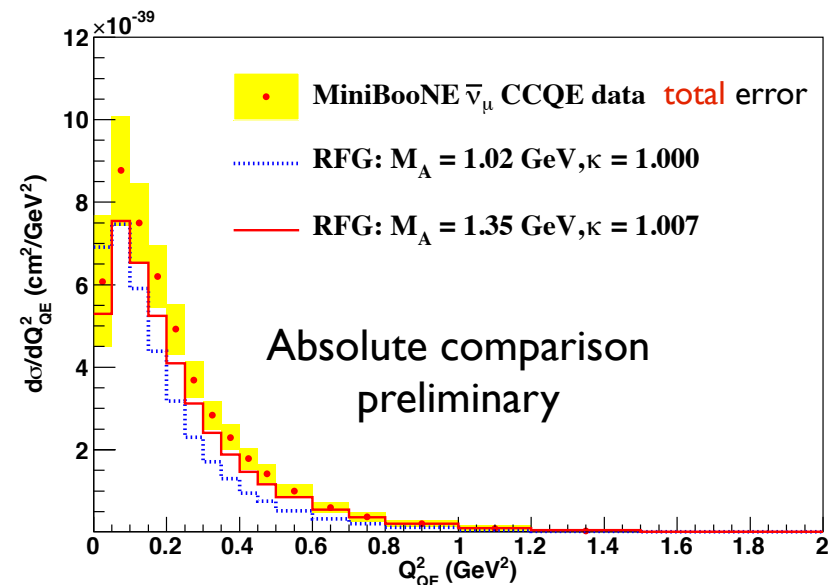
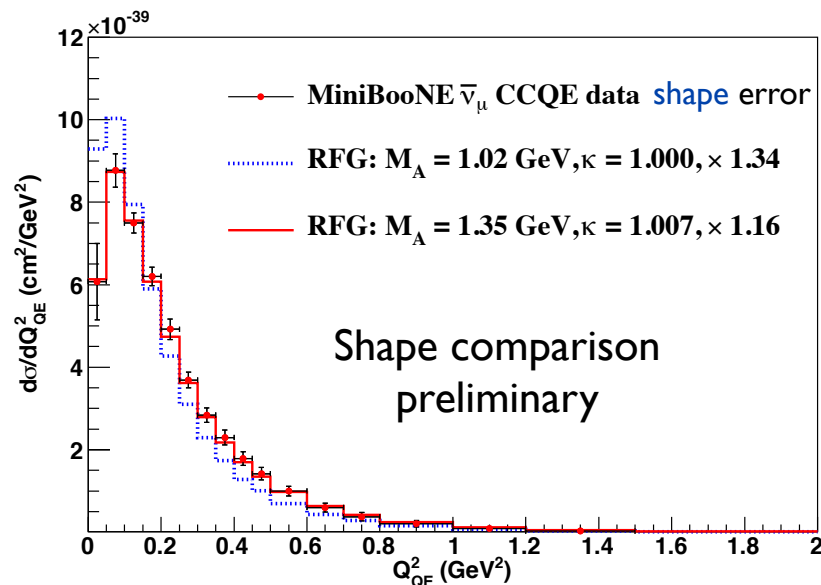
Joe Grange

NuInt 2012

Oct. 25 2012



- Under same assumptions on underlying interaction, can calculate “ Q_{QE}^2 ”



- Again, data prefers higher normalization, harder spectrum compared to expectations with $M_A = 1.0$ GeV



μ^- capture wrong-sign measurement

Joe Grange

NuInt 2012

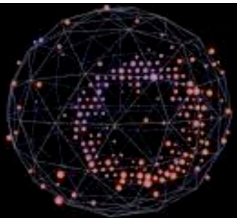
Oct. 25 2012



- Due to μ^- nuclear capture ($\sim 8\%$ in min. oil), fewer ν^- induced CC events lead to a decay electron. By adjusting the ν and anti- ν predictions, find a ν flux factor α_ν and anti- ν rate scale $\alpha_{\bar{\nu}}$

$$\mu + e^{\text{data}} = \left(\alpha_\nu \nu^{\mu+e} + \alpha_{\bar{\nu}} \bar{\nu}^{\mu+e} \right) \text{MC}$$

$$\mu \text{ only}^{\text{data}} = \left(\alpha_\nu \nu^{\mu \text{ only}} + \alpha_{\bar{\nu}} \bar{\nu}^{\mu \text{ only}} \right) \text{MC}$$



Booster Neutrino Beam

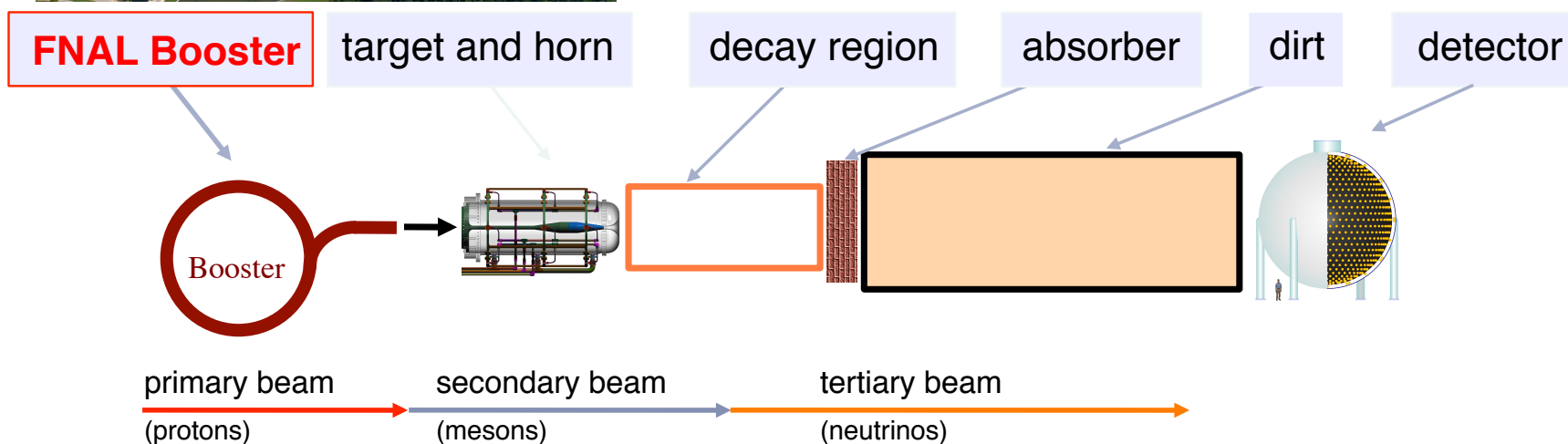
Joe Grange

NuInt 2012

Oct. 25 2012



8.9 GeV/c momentum protons
extracted from Booster incident on
beryllium target



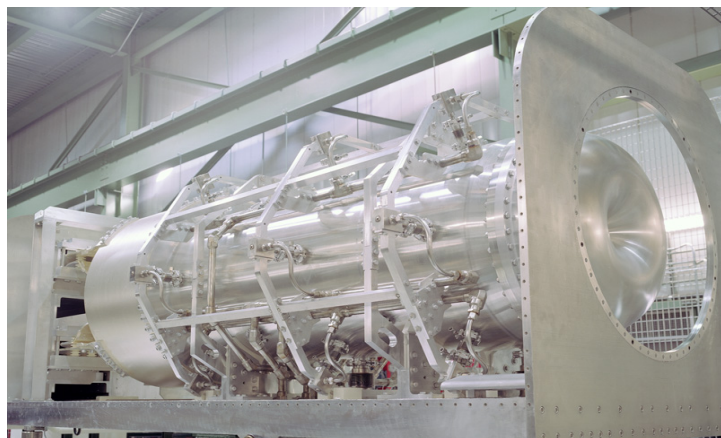


Booster Neutrino Beam

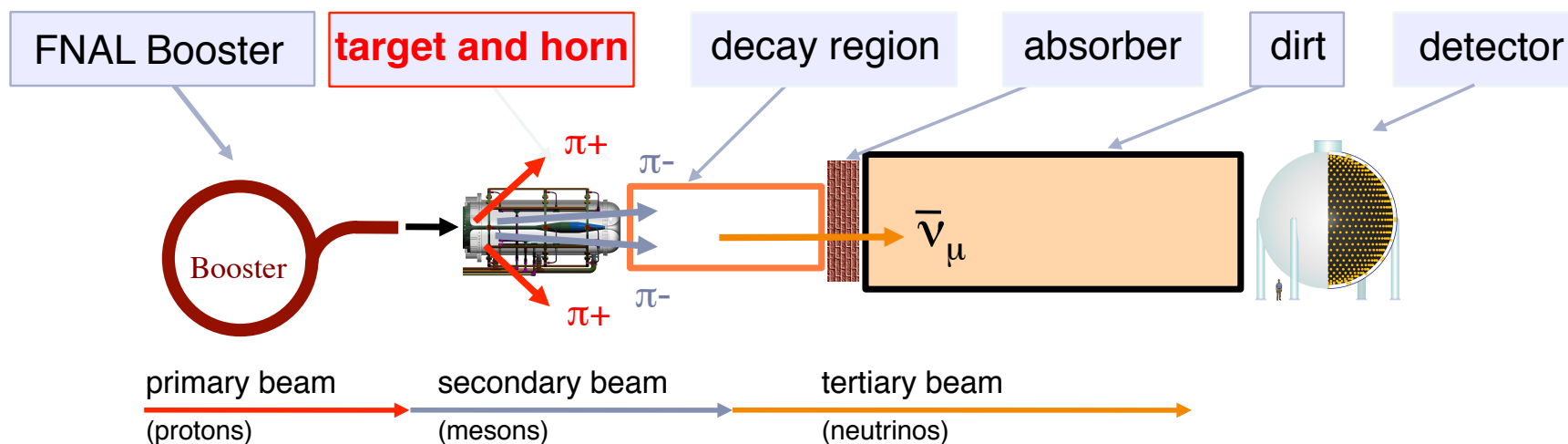
Joe Grange

NuInt 2012

Oct. 25 2012



Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons
("neutrino" vs "anti-neutrino" mode)





NCE dirt background

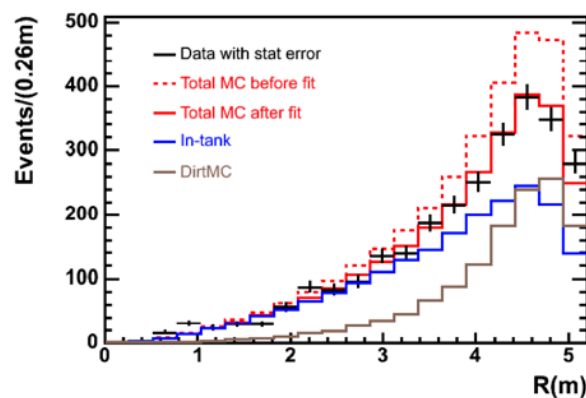
Joe Grange

NuInt 2012

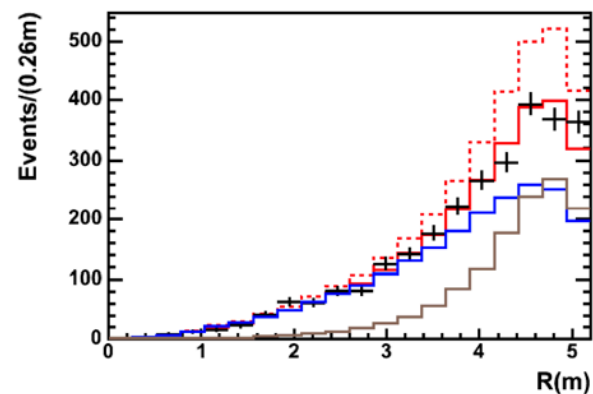
Oct. 25 2012



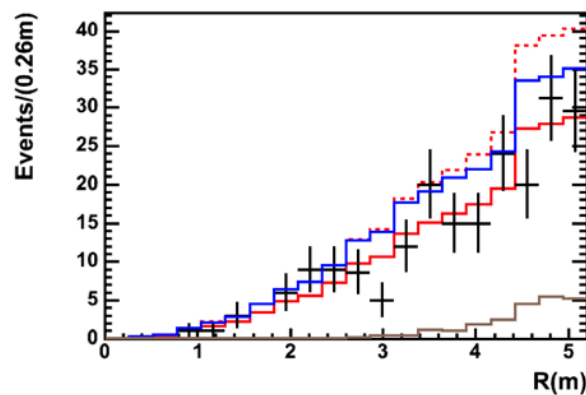
Example of radius fits in E bins



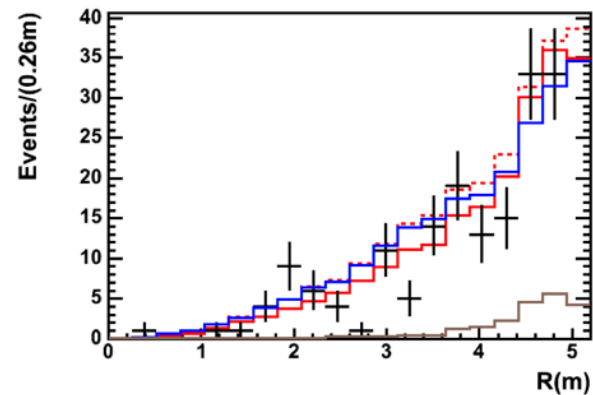
(a)



(b)



(c)



(d)



CH₂ comparison to RFG

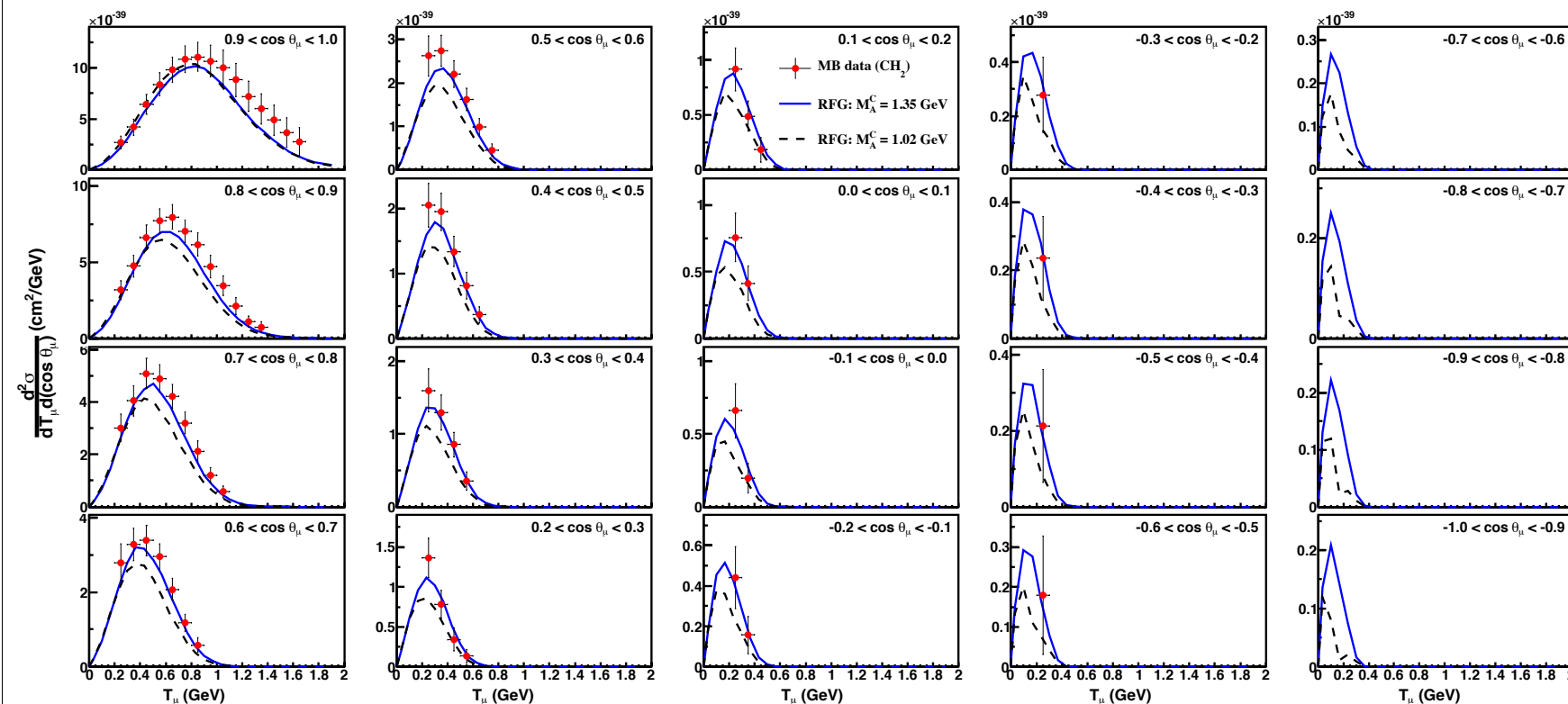
Joe Grange

NuInt 2012

Oct. 25 2012



- Data shape favors high effective axial mass
 - data ~10% high of $M_A = 1.35$ GeV
- Total uncertainty shown here





What does κ do?

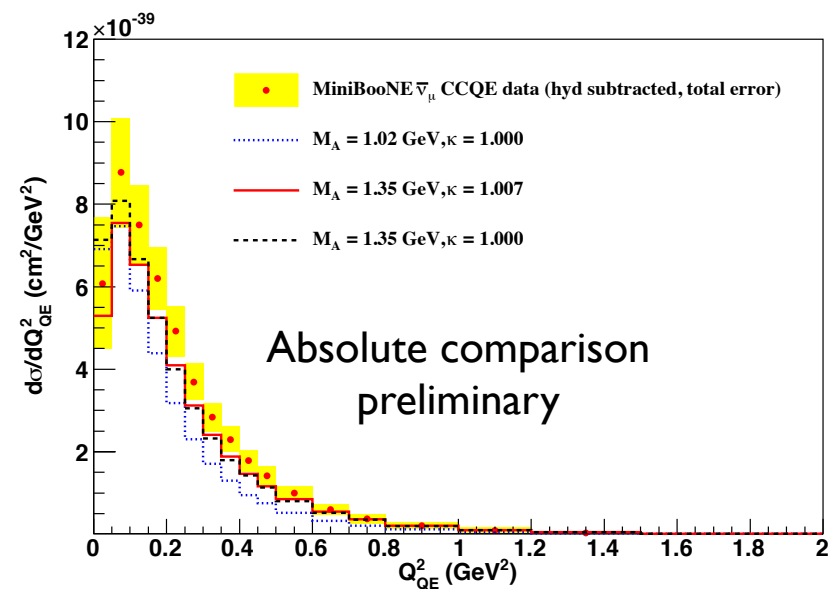
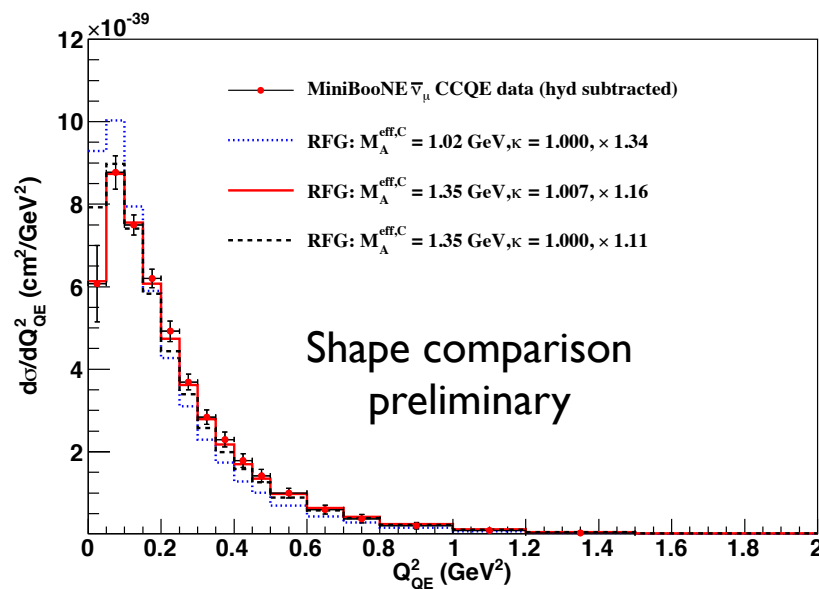
Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Small value of κ (1.007) does appreciably affect low Q^2_{QE}



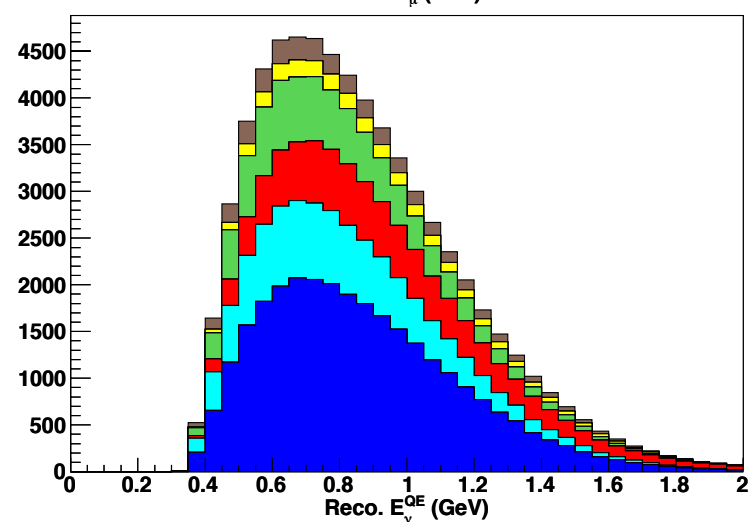
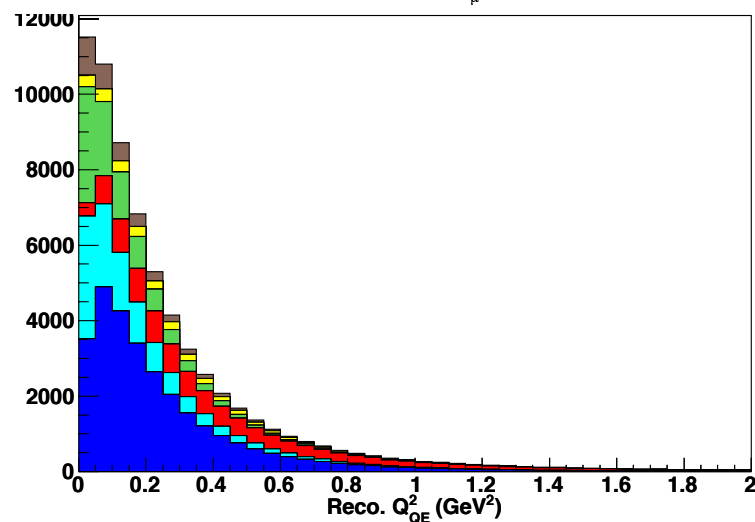
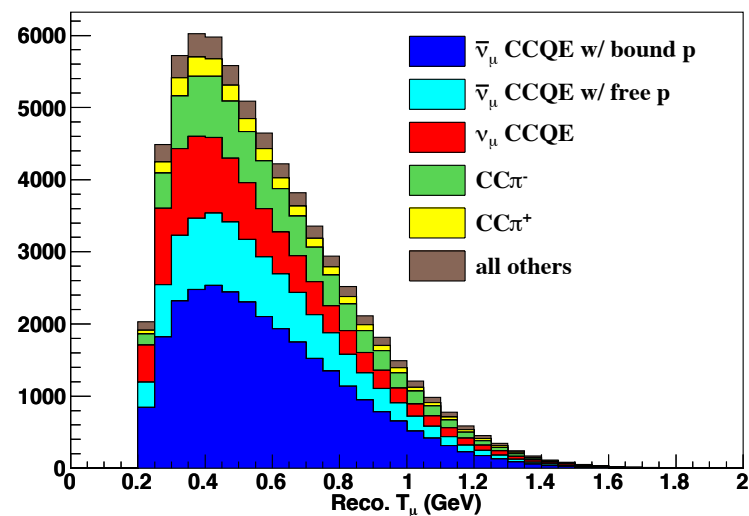
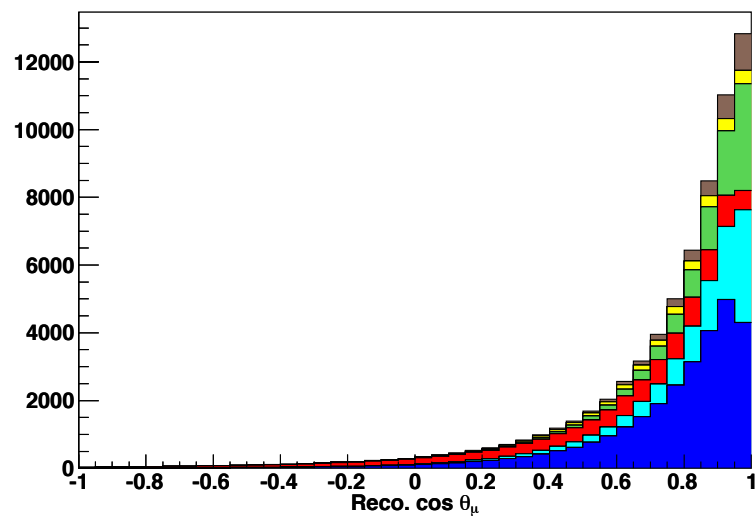


$\bar{\nu}_\mu$ sample composition

Joe Grange

NuInt 2012

Oct. 25 2012



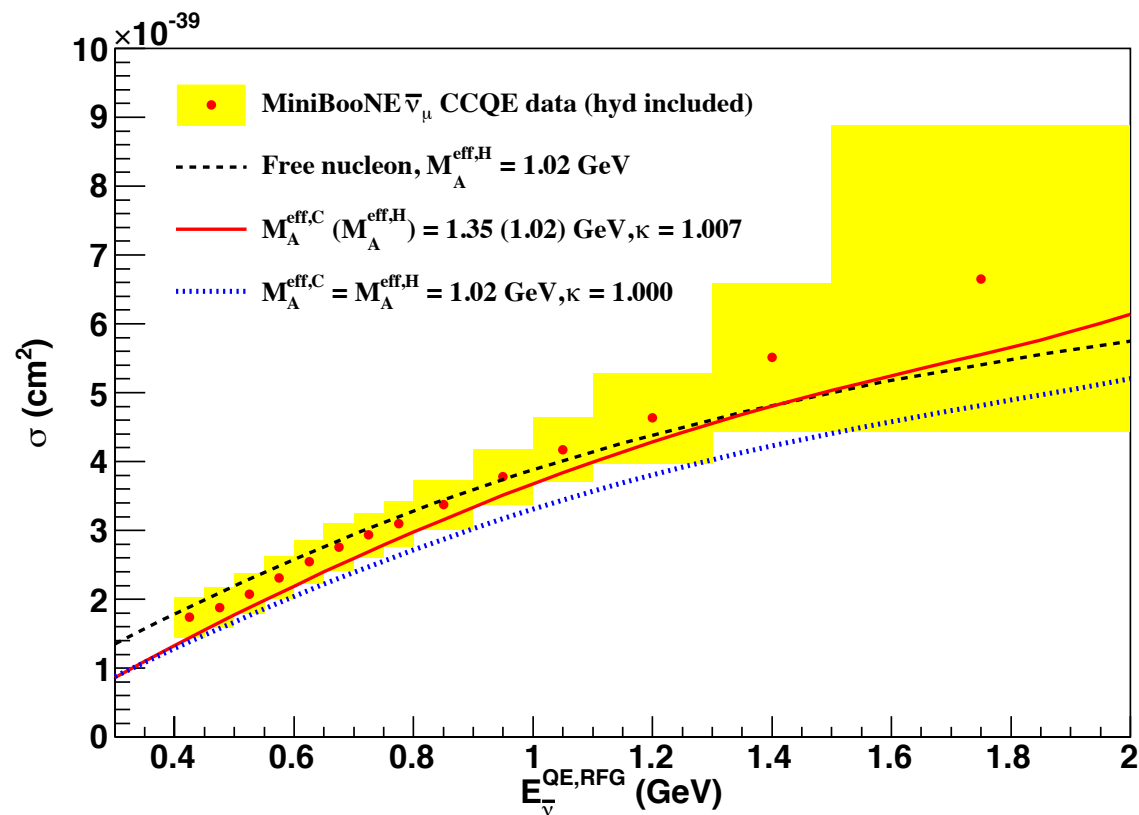


Total σ : CH₂

Joe Grange

NuInt 2012

Oct. 25 2012



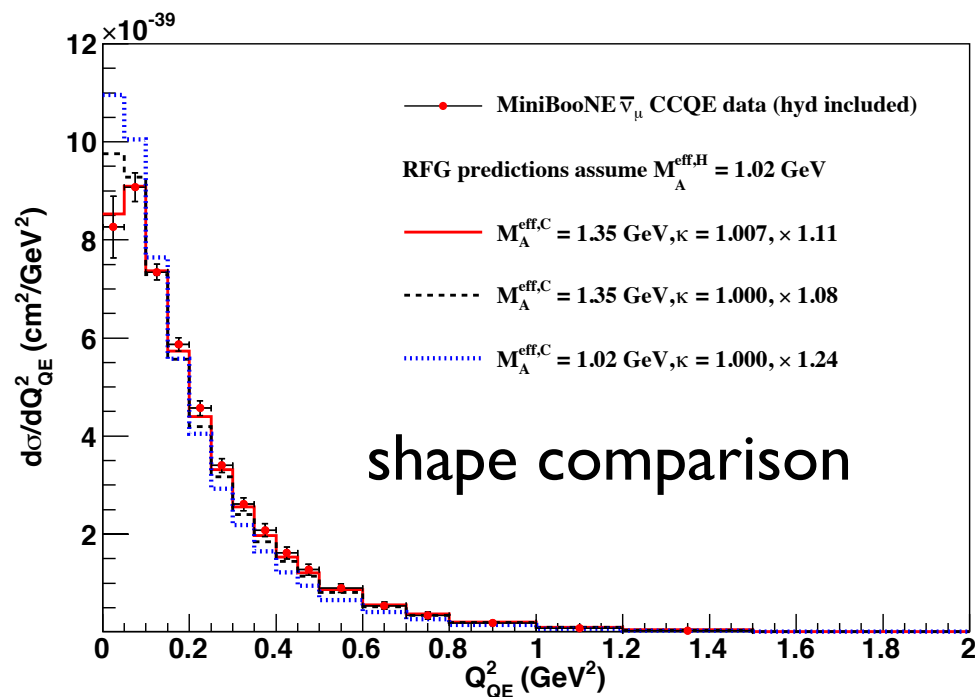


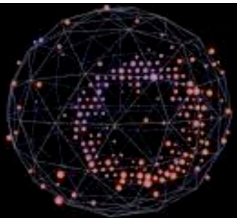
Single-differential $d\sigma/dQ^2_{QE}$: CH_2

Joe Grange

NuInt 2012

Oct. 25 2012





$\bar{\nu}$ -mode rate

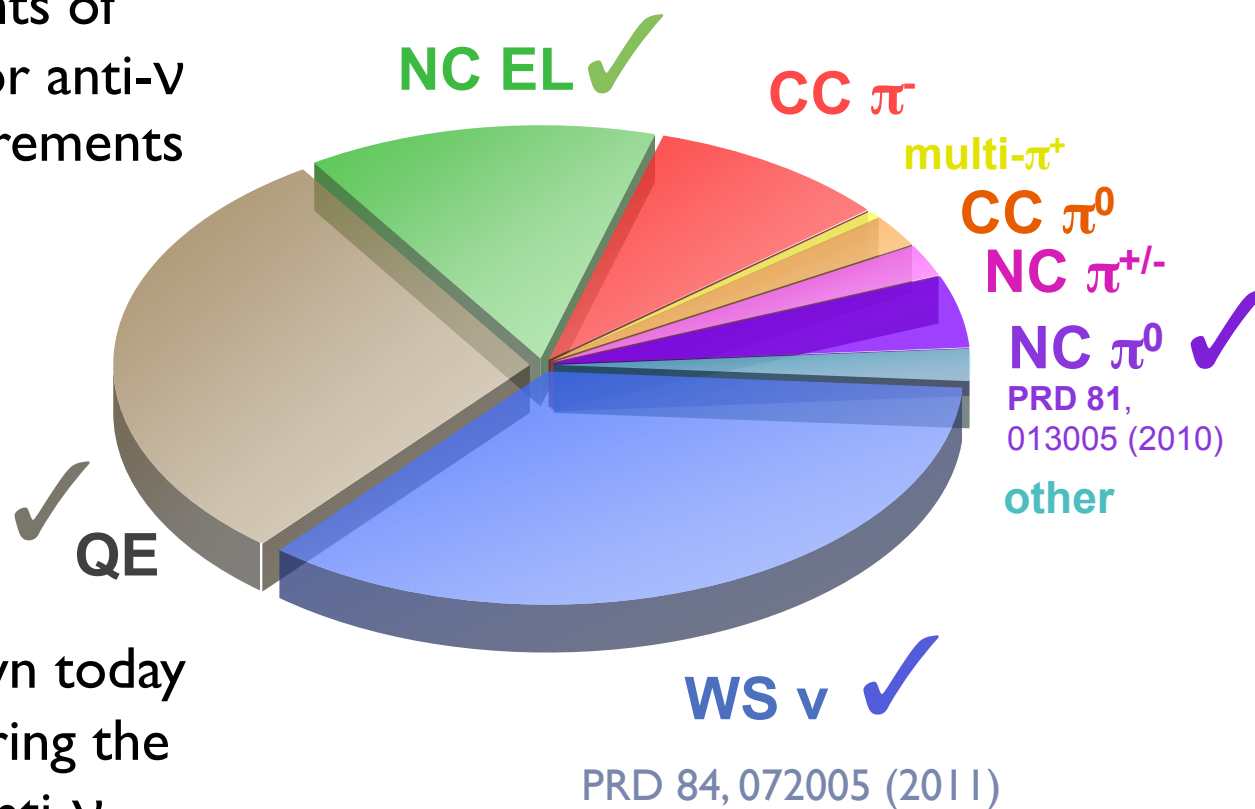
Joe Grange

NuInt 2012

Oct. 25 2012



- ▶ Robust measurements of wrong-signs allow for anti- ν CCQE, NCE measurements



- ▶ Measurements shown today (ν_μ , CCQE, NCE) bring the measured rate for anti- ν mode to **83%**



Scattering formalism



Joe Grange

NuInt 2012

Oct. 25 2012

- Use Llewellyn-Smith expressions for elastic scattering on free nuclei

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2} \left[A(Q^2) \pm B(Q^2) \times \left(\frac{s-u}{M^2} \right) + C(Q^2) \times \left(\frac{s-u}{M^2} \right)^2 \right]$$

Phys. Rep. 3, 261 (1972)

- A, B, C functions of vector and axial form factors
 - Form factors determined by external data (electron scattering, β decay), this leaves neutrino experiments one free parameter: the axial mass M_A
 - increased $M_A \rightarrow$ normalization increase, harder Q^2 spectrum
- Bound nucleon targets treated as **independent particles** subject to binding energy and global Fermi momentum
- values set by (e,e') scattering data
“Relativistic Fermi Gas (RFG)”
Nucl. Phys. B43, 605 (1972)
 - Empirical Pauli blocking scale κ



More π models



Joe Grange

NuInt 2012

Oct. 25 2012

Phys. Rev. D **76**, 033005 (2007).

